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SPACE SHUTTLE
WITH COMMON FUEL TANK
FOR LIQUID ROCKET BOOSTER AND MAIN ENGINES
(SUPERTANKER SPACE SHUTTLE)

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TABLE OF CONTENTS

ABSTRACT	PAGE 2
NOMENCLATURE	PAGE 3
INTRODUCTION	PAGE 4
BODY	PAGES 5 THROUGH 13
CONCLUSION	PAGE 14
REFERENCES	PAGE 15
APPENDIX	A THROUGH G
ACKNOWLEDGEMENT	PAGE 27
FIGURES	1 THROUGH 11
TABLES	1 THROUGH 2

ABSTRACT

An Operations and Schedule Enhancement is shown that replaces the four-body cluster (Orbiter, External Tank, two Boosters) with a simpler two-body cluster (Orbiter, Liquid Rocket Booster / External Tank). At staging velocity, the Booster Unit (liquid-fueled booster engines and vehicle support structure) is jettisoned while the remaining Orbiter and Supertank continues on to orbit, similar to the Atlas Rocket Booster. The Solid Rocket Boosters on the current U.S. Space Transportation System (STS or Shuttle) are allotted 57 days for Processing & Stack Time until Orbiter mate⁽¹⁾. The simpler two-body cluster reduces this allotted time to 20 days. Liquid Booster Systems have proven superiority over Solid Rocket Boosters in the following categories: Reliability/Safety, Resiliency (ability to resume flights after an accident), Environmental Concerns, Recurring Costs, and Evolution Potential⁽²⁾. Facility impacts to Kennedy Space Center are the same as found during the Phase "A" Design Study for replacing the Shuttle's Solid Rocket Boosters with Liquid Rocket Boosters. These impacts will occur under the given guidelines for any alteration to the four-body cluster vehicle. Retaining booster engines on the Common Fueled Tank until near orbital velocity is achieved would negate the need for Space Shuttle Main Engines (SSME's) on the Cargo Carrier of an unmanned Shuttle. As a result the number of launches available per year increases while the cost of hardware decreases. Alternative and future generation vehicles are reviewed to reveal greater performance and operations enhancements with more modifications to the current methods of propulsion design philosophy, e.g., combined cycle engines, and concentric propellant tanks.

NOMENCLATURE

ET	External Tank
GLOW	Gross Lift-Off Weight
Isp	Specific Impulse
JSC	Johnson Space Center
KLbs	1000's pounds
KSC	Kennedy Space Center-NASA
LCC	Launch Control Center
LOX	Liquid Oxygen
LH2	Liquid Hydrogen
LRB	Liquid Rocket Booster
MECO	Main Engine Cut-Off
MLP	Mobile Launch Platform
NASA	National Aeronautics and Space Administration
OMS	Orbital Maneuvering System
R & PM	Research and Program Management
SEP	Separation of Booster from Space Vehicle
SSME	Space Shuttle Main Engine
SRB	Solid Rocket Booster
STS	Space Transportation System
VAB	Vehicle Assembly Building

INTRODUCTION

The following is a theoretical concept for changing the U.S. Space Transportation System (STS or Shuttle) into a total liquid fuel system by replacing the existing Solid Rocket Boosters (SRB's) and External Tank (ET) configuration with a Common Fuel Tank Booster configuration (See Figure 1, Super-Tanker Space Shuttle).

The Common Fuel Tank Booster, given the name Supertanker, is comprised of a Booster Unit (liquid fueled engines and vehicle support structure) mounted on aft end of a large propellant tank assembly. At staging velocity, the Booster Unit is jettisoned while the remaining Orbiter and Supertank continues on to orbit, similar to the Atlas Rocket Booster. The Supertank will supply Liquid Hydrogen (LH2) and Liquid Oxygen (LOX) to the Space Shuttle Main Engines (SSME's) as well as to eight booster engines mounted on its aft dome. The Supertanker-Shuttle can achieve the same launch performance as depicted in current LH2/LOX Liquid Rocket Booster Design studies.

Liquid Booster Systems have proven superiority over Solid Rocket Boosters in the following categories:

Resiliency (ability to resume flights after an accident),	
Reliability/Safety,	Environmental Concerns,
Recurring Costs, and	Evolution Potential ⁽²⁾ .

Consequently, multiple studies were conducted to determine facility impacts at Kennedy Space Center and program-wide feasibility if SRB's were indeed replaced with Liquid Rocket Boosters (LRB's). From these studies it was concluded that a Liquid Booster System is preferable to Solid Booster Systems.

This paper proposes a propulsion design philosophy for a Common Fuel Tank Booster in which Processing, Reliability/Safety, Environmental Concerns, and Scheduling are emphasized while Performance is given secondary consideration. It is shown that Recurring Costs from Operations Check-Out and processing time are minimized when compared with four-body cluster systems.

STS-SUPERTANK EVALUATION

The Supertanker Design consists of an Orbiter (or Cargo Carrier, if used on Shuttle C), a Common Fuel Tank, given the name Supertank, of 38 Feet in diameter with a 76 foot long liquid Hydrogen Tank barrel section, and a Booster Unit made up of eight-500 Klb thrust LH2/LOX engines (See Figures 1 & 4). Since data is readily available on these LRB engines⁽³⁾, they are referred to throughout this paper. At staging velocity, the Booster Unit is jettisoned while the remaining Orbiter and Supertank continues on to orbit, in a similar manner to the Atlas Rocket Booster. It may be noted that Operations would be minimized if only one liquid booster engine with one LOX and one LH2 turbopump was used⁽⁴⁾. However, greater reliability is realized if four⁽³⁾ 1,100,000 lb thrust LH2/LOX burners with two LOX and two LH2 turbopumps were used instead, e.g., USSR Energia.

A propulsion evaluation was performed for the SUPERTANKER-SHUTTLE Vehicle using parameters from SRB-STS (see Appendix A). Gross Lift-Off Weight (GLOW) was calculated as 3838 Klbs. The total Vehicle Dry Weight at Launch was calculated as 535 Klbs, and the total Common Fuel Tank Fuel Mass as 3304 KLBs (472 LH2 / 2832 LOX). The LH2 tank barrel is limited to 76 foot length for use with existing Orbiters. The SUPERTANKER's diameter is then set at 38 Feet. (As calculated in Appendix B)

The size of the Supertanker is somewhat larger than the existing Space Shuttle External Tank (ET). Current ET's are 27.5 feet in diameter with a 76 foot long LH2 tank barrel section. The SUPERTANK will be 7.9 feet shorter due to a shorter LOX Tank and absence of the SRB Thrust Beam⁽⁵⁾. (See Appendix B and Figure 5).

DIMENSIONS

LENGTH OF LOX TANK	37.5 Feet
LENGTH OF LH2 TANK	104.8 Feet
TOTAL LENGTH OF SUPERTANK	146 Feet
LENGTH OF BOOSTER UNIT	13.0 Feet
TOTAL LENGTH OF SUPERTANKER	159 Feet

Unlike other Liquid Rocket Booster concepts, the Booster Unit contains all the booster engines, avionics, and controls in one compact, lightweight package. Since the Booster Unit is in a single compact package that could be adapted readily for dry (land base) recovery. A recovery attempt may prove feasible if the total price of the Booster Unit is greater than about \$80 million.

An additional reason for using the 38 foot diameter LH2 tank is its potential use as a Space Station Component. Unlike the current External Tank, the Supertanker uses a 31.9 inch diameter fuel line on its aft tank dome, which would provide somewhat easy access for Hydrogen Tank entry (See Appendix C).

RELIABILITY AND SAFETY

The U.S. Space Shuttle is the first vehicle in history that uses Solid Rocket Boosters on a manned mission. NASA chose to use SRB's based on projected low development costs compared to liquid systems. The development costs were indeed held down by designing the Solid Rocket Boosters from adopted designs from the Minuteman and Titan programs ⁽²⁾. However, Recurring Costs and processing time were grossly underestimated.

Liquid systems have a greater reliability than solid systems. Liquid systems' reliability is inherited due to their ability to perform a controlled shut down and their easy ability to perform many tests for flight readiness at various levels of systems complexity, i.e., component, full up engine, and static firing of the entire flight system as in a Flight Readiness Firing (FRF). An indication of this ease of testing is obtained by comparison of the number of hot fire tests that have been conducted on the Main Propulsion System and Solid Rocket Boosters, more than 1350 versus 15 ⁽²⁾. In addition, the severity of a failure in a solid system results in a higher probability of loss of vehicle. A liquid fueled booster system comprised of four engines that can obtain an Abort-to-Orbit with one engine out, has a calculated reliability of 0.9935 ⁽³⁾. This can be compared to the reliability of 0.9765 demonstrated by the 174 Titan and 50 Shuttle flights with segmented Solid Rocket Motors.

ENVIRONMENTAL CONCERNS

The Solid Rocket Boosters each contain 1,112,665 Lbs of propellant ⁽⁶⁾ which is composed of:

69.72% oxidizer, Ammonia Perchlorate (NH_4ClO_4),
 16.00% fuel, Aluminum powder (Al),
 0.28% catalyst, Iron Oxide (Fe_2O_3),
 12.04% hydrocarbon binder/fuel ($\text{C}_{6.884}\text{H}_{10.089}\text{O}_{0.278}\text{N}_{0.264}$)
 1.96% hydrocarbon binder/fuel ($\text{C}_{6.15}\text{H}_{6.97}\text{O}_{1.17}\text{N}_{0.03}$).

Each flight of a Solid Rocket Booster Shuttle produces:

EXHAUST PRODUCT	FORMULA	ATOM #	MOLE FRACTN % ⁽⁷⁾	MASS FRACTN %
Aluminum Oxide	(Al_2O_3)	102.0	7.98	30.25
Carbon Monoxide	(CO)	28.0	23.16	24.10
Carbon Dioxide	(CO_2)	44.0	2.15	3.52
Chlorine atom	(Cl)	35.5	0.17	0.22
Iron Dichloride	(FeCl_2)	126.9	0.09	0.42
Hydrogen atom	(H)	1.0	0.43	0.02
Hydrochloric acid	(HCl)	36.5	15.60	21.17
Hydrogen gas	(H_2)	2.0	27.84	2.07
Steam	(H_2O)	18.0	14.09	9.43
Nitrogen gas	(N_2)	14.0	8.42	8.76
other	average	17.0	0.07	0.04
TOTAL			100.00	100.00

30.21% by mass of exhaust products condenses.

The above calculations were performed assuming the following conditions:

Chamber Pressure 685.0 psia,	Exhaust Pressure 14.85 psia
Chamber Temperature 6113 R,	Exhaust Temperature 4100 R
Chamber Density 0.296Lbm/ft ³ ,	Exhaust Density 0.00987Lbm/ft ³ ,
Throat Temperature 5763 R,	Exhaust Velocity Mach 2.83 or 18,103 mph

As shown above, over one half (volume) of the exhaust is combustible gas. Over one fifth (mass) of the exhaust is hydrogen chloride gas, which produces dangerous hydrochloric acid when combined with water on the ground, but more importantly, produces ozone destroying chlorine ions in the upper atmosphere when it is exposed to ultraviolet light from the sun. The Solid Rocket Boosters were designed years before first mention of deteriorating Ozone concerns. Indeed, it was through the study of SRB exhaust plumes that brought the subject to a head. (8)

Each Space Shuttle Main Engine consumes 147 lbs per sec of Liquid Hydrogen and 882 lbs per sec of Liquid Oxygen. Since the oxygen to fuel ratio is 6-to-1, each SSME will produce the following exhaust products:

<u>EXHAUST PRODUCT</u>	<u>FORMULA</u>	<u>ATOM #</u>	<u>MOLE FRACTN #</u>	<u>MASS FRACTN #</u>
Hydrogen gas	(H ₂)	2.0	0.41	3.57
Steam	(H ₂ O)	18.0	99.59	96.43
other	(H, OH, O)	N/A	<u>trace</u>	<u>trace</u>
		TOTAL	100.00	100.00

SCHEDULING

Reference Figure 9⁽¹⁾, this chart can be used to estimate the time required to process a Supertanker for Launch. It is assumed that the Supertanker arrives at KSC with its booster unit already mated to the Supertank. Since a Supertanker is similar in many aspects to LRB's, a generic LRB Process Flow would be comparable to a Supertanker Process Flow. However, it is shown below how process flow time (barge offload to orbiter mate) for a Supertanker is reduced from 33 to 20 days when compared with Liquid Rocket Boosters.

- 1) Standalone check-out will not change from 18 days
- 2) MLP Mate & Close-Outs will be halved since 1 mate is performed instead of two; A savings of 2 days.
- 3) If the Booster Unit is mated at the factory with the tank, then there would not be an ET mate with its associated Close-Outs for a savings of 11 days.

NOTE: No changes should occur to the 5 days allotted for Orbiter Mate and Integrated Systems Test. This test is essentially an Orbiter systems test and with respect to time, independent of the propulsion system used.

Also, 2 days will be cut off the LRB Flow at the PAD since only one fuel and one oxidizer are loaded into one tank each. The Pad Schedule for the Supertanker would then parallel the existing SRB/STS Pad Schedule.

By using a common fuel tank vehicle as described above, the 80 days allocated for barge offload, Processing & Stack Time, Orbiter mate, and launch for the SRB-STS is reduced to 45 days for the Supertanker. Since there are two integration cells, two launch pads, and assuming there will be two check-out cells and two MLP's for the Supertanker, the Supertanker could support a manned shuttle launch every 22 days or 16.2 Launches per year. However, since 20 days are required for processing until mate, 36 Supertankers could be made available each year if required.

STS SRB vs SUPERTANKER COST COMPARISON

PROCESSING COSTS

The amount of workload and cost per flight to process the SRB's at KSC can be found in Table 1 as 100,716 man-hours and \$1,925,365. Similarly in Table 2 the workload and cost per flight to process the LRB's can be found as 107,701 man-hours and \$1,979,000⁽¹⁾. Although the workload to process engines will not vary between the LRB's and the Supertanker, since both contain eight engines per mission, the total man-hours will be less for the Supertanker because only one fuel and one oxidizer tank is processed instead of three. The processing costs for the Supertanker could actually be less than stated above since Engineering Support is a large portion of this cost and there already exists a Liquid Engine Support group at KSC for the Orbiters SSME's.

PROPELLANT COSTS

Propellant costs, \$22.4 million, amount to 4% of the Total Recurring Costs⁽⁹⁾ for the SRB-STs. Using hydrogen and oxygen as the only propulsion propellants, this cost would be reduced to \$611,210 (See Figure 6^(9 & 14) and Appendix D). However, the propellant cost listed in TABLE 3 is for the External Tank and Orbiter OMS Pods. SRB propellant is included in its own hardware costs.

SUPERTANKER HARDWARE COST

The average unit cost of each 16 foot diameter LRB was stated by General Dynamics as \$51 million with the four engines representing 42% of this cost⁽³⁾ (See Figure 7). If a 38 foot diameter LRB with eight of these same engines was built, it can be reasoned that it would cost 2.375 times (38 ft diameter circumference is 2.375 times greater than a 16 ft diameter) more to build a 38 foot diameter tank as it would be to build a 16 foot diameter tank. However, the eight engines with an unit cost of \$5,355,000 will remain the same. If it is assumed the Design, Development, Testing, and Engineering as well as the 244 planned flights remains the same, then the Basic Supertanker Unit Cost can be calculated to be \$113.1 million, which means the engines now represents 37% of the total hardware costs.

It is concluded from this method that the hardware cost for the Supertanker is the same as the \$110 million, as found in TABLE 3 below, for the External Tank and two SRB's it replaces. Therefore, the Total Recurring Costs (Processing, Propellant, and Hardware) for operating the Supertanker-Shuttle would amount to the same as the Total Recurring Costs for operating the Current SRB-Shuttle, if the same flight rate was maintained.

Currently, the same amount of time to process an Orbiter is required to process a set of SRB's, 180 shifts for an Orbiter versus 171 shifts for an SRB. Thus, the flight rate cannot be increased unless a new SRB Stacking facility (off-line) and new Orbiter processing bay were built. However, the Supertanker could support a flight rate of 36 launches per year (12.8 manned Shuttle launches and 23.2 unmmanned Cargo Shuttle launches). All but the first four categories listed in TABLE 3 are approximately the same regardless of the number of launches. Therefore, the result of increasing the flight rate as listed above would greatly reduce the cost per flight and cost per pound of payload to orbit. Assuming the manned Shuttle has a payload capacity of 70,000 lbs and a Cargo Shuttle has a payload capacity of 160,000 lbs, the cost per pound of payload to orbit would then be \$1470. In comparison, the cost per pound to orbit for 1985 Fiscal Year was \$5470.

TABLE 3⁽⁹⁾

(FY-85 STS TOTAL COSTS FOR 8 FLIGHTS)			
SRB	\$ 464.2 Mill	Flight Operations (JSC)	\$ 345.3 Mill
Eternal Tank	\$ 415.8 Mill	Launch Operations (KSC)	\$ 347.5 Mill
Orbiter Hardware	\$ 162.6 Mill	Propellants	\$ 30.3 Mill
Crew Equipment	\$ 36.3 Mill	SSME Testing(Stennis SC)	\$ 51.6 Mill
Ground Support	\$ 24.1 Mill	Contract Administration	\$ 17.1 Mill
	SUBTOTAL	\$1894.8 MILLION	
plus			
NETWORK SUPPORT	\$ 20.4 Million		
R & PM (NASA)	<u>\$ 274.2 Million</u>		
FY-85 TOTAL COST	\$2189.4 Million (in 1985 dollars for 8 flights)		
	or \$ 273.5 Million per flight		

SUPERTANKER FACILITY IMPACTS⁽¹⁾

From Lockheed's analysis in the LRB study it was determined that the following major KSC impacts would occur for any major alteration to the current Space Transportation System:

- 1) New Integration Cell in the VAB's High Bay 4 (cost \$33.4 mil)
To allow non-interference with ongoing manned Shuttle schedule missions.
- 2) New Horizontal ET/LRB Processing Building and Engine Shop (cost \$124.6 mil)
New Integration Cell would replace today's ET Processing Cell
- 3) Two New Mobile Launch Platforms (cost \$200 mil each)

Less expensive than modifying current MLPs and would allow non-interference with manned Shuttle missions.
- 4) Additional LH2 Storage Tanks at both Pads (cost \$117 mil each)
Additional Tanks would allow 24 Hour Scrub Turnaround
- 5) Launch Control Center modifications (cost \$14 mil)
LCC would need modifications to preform tests to the new engines.

Total first line facilities cost \$825.7 million⁽¹⁾.

Hold-Down Post Placements Problems encountered during the LRB study would be eliminated because the weight of the vehicle is distributed about a single, centrally located structure and the exhaust plume is generated from a single concentrated source. (See Figure 8).

SUPERTANKER EVOLUTION POTENTIAL

The same propulsion design philosophy (of one oxidizer - one fuel tank and stage only propulsion) that was used to design the Supertanker-Shuttle could also be applied to smaller commercial vehicles. See Figure 11.

A Delta Class (7,600 Lbs to Low Earth Orbit) vehicle could be designed. (See Appendix E). GLOW was calculated to be 173,100 lbs and the 10 Foot diameter LH2 and LOX tanks would have a length of 72.9 Feet and 26.0 Feet respectively.

A Shuttle-Z Class (450,000 lbs to Low Earth Orbit) vehicle could be designed. (See Appendix E). GLOW was calculated to be 10,557,000 lbs and the 60 Foot diameter LH2 and LOX tanks would have a length of 123 Feet and 44.0 Feet respectively.

In similar calculations, a Titan Class (42,900 Lbs to Low Earth Orbit) could also be designed. (See Appendix E). Glow was calculated to be 990,900 Lbs. If a vehicle length of 111.5 feet is used with 16.5 feet of that length allotted for engines and propulsion system, then calculations are performed to yield a vehicle diameter of 24.9 feet. If this vehicle was "man rated" the ten crew member Personnel Launch System (PLS) could be launched with the inherited better reliability and cleaner vehicle than a PLS utilizing the current Solid Rocket/Hypergonic powered Titan vehicle.

MULTI-BOOSTER UNIT STAGES MANNED SHUTTLE

The Thrust-to-weight ratio after booster separation on SRB-STS is simply: Thrust 3 SSME's vacuum / Vehicle Mass after Booster SEP. Both values can be found in appendix A to give 1410 Klbs/1573 Klbs which equals 0.896 : 1.

To keep this Thrust-to-Weight ratio the same on the Supertanker, fuel had to be sacrificed due to a greater dry weight to orbit (from a heavier ET). To increase vehicle performance, the six outer Booster Engines and support structure would be jettisoned (approximately 100 klbs) at Mach 4.5. This will leave two 500 Klb thrust booster engines with the SSME's to obtain 2310 Klbs / 1583 Klbs or 1.46-to-1 thrust-to-weight ratio. The two booster engines could be retained until 3 G acceleration is obtained again. For a thrust of 2310 Klbs, 3 G acceleration is achieved at a vehicle weight of 770 Klbs. This amount of fuel (813 Klbs) would be consumed in 158 Seconds after Booster Unit Separation.

SHUTTLE - C

If the two retained booster engines are kept until orbit, there would be no reason to have two or three SSME's on an unmanned payload carrier (e.g., Shuttle-C). Since there is no thrust from the SSME's, the minimum thrust-to-weight limitation of 0.896 : 1 would now require Booster Unit Separation at a velocity greater than that for the Manned Supertanker Shuttle. The current Shuttle-C concept contains two or three SSME's, valued at \$35 to \$55 million each when new, which have flown the designed 10 flights. However, since the Orbiter takes 60 days to process, the manned shuttle can only be launched 12.8 missions per year. As a result only six SSME's will become available to allow three Shuttle-C flights.

MULTI-BOOSTER UNIT STAGES
SHUTTLE - C cont

The Solid Rocket Boosters on the current U.S. Space Transportation System require 57 days for Processing & Stack Time until Orbiter mate. This is the same amount of time required to process an Orbiter. Unless an off-site SRB stacking facility is built, a Shuttle-C composed of the current concept would interfere with the ongoing Manned Space Operations. The proposed Advanced Solid Rocket Motor would shorten this processing time to 42 days⁽¹⁰⁾ and would allow for 2.5 launches more per year than can be flown with Orbiters. Since only 20 days are required to process the Supertanker until Orbiter or Payload Carrier mate, it would be capable of not only supporting the 12.8 Manned Shuttle launches per year, but also could support 23.7 Shuttle - C launches per year. (See Table 4).

Shuttle-C has been determined to require 83 shifts (42 two-shift days or 28 three-shift days)⁽¹⁰⁾ if two or three SSME's are installed at KSC. However, a Cargo Carrier requiring no Main Propulsion System Engines could be used if two or three Booster Engines were retained on the Supertanker. A Cargo Carrier without any MPS engines would reduce the 83 activities per flow for a SSME Cargo Shuttle to 43 activities. At three shifts per day, it would require:

24 days to process Cargo Carrier and install payload

4 days to integrate Cargo Carrier to Supertanker

7 days at pad

for a total of 35 days from Cargo Carrier on dock to launch⁽¹¹⁾.

TABLE 4

<u>BOOSTER</u>	<u># DAYS TO MATE</u>	<u># of MANNED SHUTTLES IT COULD SUPPORT</u>	<u># OF SHUTTLE-C IT COULD SUPPORT</u>
Solid Rocket Booster	57 Days	12.8*	0.0
Advanced Solid Rocket	42 Days	12.8*	2.5
Supertanker	20 Days	12.8*	23.5**

* NOTE: Assumes only two Orbiter Processing Facilities, 180 activities per flow, and three shifts per days.

** NOTE: Assumes Shuttle-C does not interfere with Manned Shuttle Pad Operations.

COMBINED CYCLE

Another Performance Enhancement for the near-term would be replacing four Booster Engines with an Air Breathing Nozzle under the External Tank (See Figure 2). In this concept, air would be induced to flow through the nozzle by a change of momentum from the hot exhaust flumes of the remaining five booster engines (NOTE: the SSME's on the Orbiter have been eliminated). As the air passes the throat of the nozzle, hydrogen is injected and ignited, thereby creating thrust in a somewhat similar manner as a Ram Jet.

By using such a system, thrust created by the Air Breathing Nozzle has a Specific Impulse (Isp) that varies from 1600 to 3500 seconds^(12 & 15). It can be shown that after 15 seconds into flight, air is self induced through the nozzle, therefore the Booster Rocket Engines thrust could be reduced or eliminated.

If the Shuttle's Trajectory is altered so that it remains in the atmosphere for much of the initial boost phase (first 145 seconds), the Air Breathing Nozzle could provide much of the required thrust. When a performance analysis is performed using data obtained in Figure 9, and assuming the Booster Rocket Engines are shutdown after 15 seconds and not restarted until Booster Unit Separation at Mach 6, GLOW is calculated to be 1495 Klbs. (See Appendix F)

The previous performance characteristics would require an External Tank of 145 foot length x 27.5 foot diameter that would contain 282.9 Klbs of LH2 and 796.6 Klbs of LOX. In comparison to today's conventional External Tank, the ET required for the above Combined Cycle Shuttle would require the following: The LH2 tank will need to be lengthened by 22 feet; the LOX tank could be shortened by 6.3 feet; and the Intertank will be shortened by 42.957 inch (3.6 feet) because the SRB Thrust Beam could be eliminated. (See Figure 5)

SUPERTANKER II

An Operations Enhancement could be accomplished by creating a "Second Generation" Supertanker vehicle: (See Figure 3, SUPERTANKER II)

A Second Generation Supertanker would employ concentric LOX/FUEL tanks. A 19.5 foot diameter LOX tank would be placed inside a 38 foot diameter torroidal shape LH2 tank. Both insulated tanks would be thermally independent of each other by a 1 inch air gap between tanks and each tank would have a barrel section of 120 foot length.

The orbiter (or payload) would be placed forward of the propellant tanks. Loads present on the LOX tank aft end would require a much thicker tank skin than currently used on today's shuttle. The LOX tank would then become the most suitable load bearing structure. However, for pad simplicity the LOX tank would not need to be pressure stabilized, as are the Atlas Booster, and Centaur.

The forward end of the LH2 tank would need to be independent of the LOX tank forward end, because the LH2 tank is at a colder temperature. This would allow the LH2 tank to shrink more than the LOX tank. With no loads present on its forward end and only hydrostatic loads present on its aft end, the LH2 tank skin may become extremely lightweight.

Another three 500 KLB thrust Booster Engines would need to be added to the Booster Unit, since the SSME's will have been eliminated. Of course, now three booster engines must be retained until MECO.

An "active" pressurization system has been replaced by a "passive" system. In this system "hot" LH2 at 39 degree Rankine and 6 psig and LOX at 168 degrees Rankine and 6 psig⁽¹³⁾ is loaded into the vehicle. As the vehicle ascends and consumes fuel, the liquid propellants will "flash boil." That is, the liquid near the liquid/gas surface will boil whenever the pressure tries to go below 6 psig. In doing so, it will pull energy from its surrounding liquid at 9,730 Kilowatts in the LH2 environment and 5,750 Kilowatts in the LOX environment. This increases the surrounding fluids' density, causing it to sink to the tank bottom where the fuel inlet is. Consequently, only the warmest, least dense liquid is at the surface. Any added heat from outside sources only enhances the process. (See Appendix G).

Concentric fuel tanks would eliminate the geyser and pogo concerns associated with long feedlines. The LOX tank would be located closer to the ground which, could eliminate the need for large propellant pumps during loading.

CONCLUSION

A substantial schedule and manpower savings could be realized if the United States Space Shuttle was configured with a Common Fuel Tank with aft mounted booster engines (a Supertanker). Though the hardware and processing cost for the Supertanker would parallel the existing Space Shuttle's SRB's, all costs for the Space Shuttle's External Tank would be eliminated. Furthermore, when the Supertanker is compared with proposed LRB concepts, Launch Operations are reduced considerably because only one set of oxidizer and fuel tanks are processed instead of three. The size of the fuel tank does not affect the magnitude of manpower required to process it. The most appealing benefits from the Supertanker concept are its reduction in cost per flight (more flights could be made per year), reduced environmental impacts (its only by-product is water), and greater reliability (as inherited in multi-engine liquid systems). Also, the Supertanker will make the Shuttle-C concept highly feasible since it is not restrained by the supply of used SSME'S. The same facilities impacts to KSC would occur with the Supertanker (or almost any new concept different from the current configuration) as with the Liquid Rocket Booster Program.

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APPENDIX A

page 1 of 3

To find an unknown propulsion parameter of a vehicle the following calculations are made:

EQU 1.) $V_b = G * I_{sp} * \ln(M_{ini} / M_{fin}) - k * G * t$
where

V_b = Velocity of vehicle after fuel has been expended
 G = Gravitational constant = 32 feet per sec per sec
 I_{sp} = Specific Impulse of total vehicle (lbf / lbfm/sec)
 M_{ini} = Mass of initial vehicle
 M_{fin} = Mass of vehicle after fuel has been expended
 t = Amount of time to achieve V_b after lift-off
 k = Correction Factor - derived by considering the amount
 of time thrust is used to overcome gravity.

Using known characteristics from SRB-STS to find unknown characteristics of Supertanker Shuttle.

<u>SRB-STS (6)</u>		<u>SUPERTANKER</u>
220,092 lbs	Orbiter Inert & OMS Prop	220,092 lbs
51,246 lbs	Payload	70,000 lbs
66,760 lbs	External Tank or Supertank	120,300 lbs
376,416 lbs	SRB (dry weight)	
	Booster Unit (Structure)	73,004 lbs
	Booster Unit (eight-engines)	54,533 lbs

714,514 lbs	Total Vehicle Inert Weight @ Launch	537,929 lbs
338,098 lbs	Mass at MECO	410,392 lbs
1542 Klbs	Mass after Booster Separation	1542 Klbs
269 (228) Sec	Booster Isp in Vac (S/L)	427 (382) Sec
2397 Klbs	AVE Booster Thrust (Boost Phase)	4205 Klbs
	Booster Thrust Vac (S/L) * 8	4508 (3902) Klbs
SSME Parameters (17)		
453.5 (361) [407] Sec	SSME Isp in Vacuum (S/L) [Ave Boost Phase]	
1413 (1131) [1272] Klbs	SSME Thrust in Vacuum (S/L) [Ave Boost Phase]	
6986 lbs	SSME Weight	
1590 Klbs	External Tank Fuel of SRB-STS	
4525 Klbs	Gross Lift-Off Weight (GLOW) for SRB-STS	
123.6 Seconds	Time to Booster Separation	121.3 Seconds

Average Thrust and Average Specific Impulse was derived by assuming the vehicle was reacting against a degrading air pressure during boost phase.

STS-SRB EVALUATION

Using Equation 1) a propulsion analysis of today's SRB-STs will revealed parameters which can be correlated with the Supertanker. The velocity gained by the SRB-STs after Booster Separation is calculated by the following:

Using Eq 1):

$$\begin{aligned} V_{meco} &= (32 \text{ ft/sec}^2) * 453.5 \text{ Sec} * \ln (1542/338) - 0 \\ &= 22,026 \text{ Ft/sec} \end{aligned}$$

Although, it was assumed that "k" was zero in the above equation, in actuality it is finite. When the above result is correlated with the Supertanker, this parameter nearly cancels out.

Because the Specific Impulse is different for the SSME's and the SRB, the Average Vehicle Isp during the boost phase is calculated by doing the following:

$$\text{EQU 2) Average Vehicle Isp} = \frac{\{ (Isp_1 * Thrust_1) + (Isp_2 * Thrust_2) \}}{(Thrust_1 + Thrust_2)}$$

$$\begin{aligned} \text{Ave Veh Isp} &= 310.3 \text{ Seconds} \quad \text{from the calculation} \\ &\{ (407\text{sec} * 1272\text{Klb}) + (259\text{sec} * 2397\text{Klbs}) \} / (1272\text{Klbs} + 2397\text{Klbs}) \end{aligned}$$

Using Eq 1):

$$\begin{aligned} V_{\text{boost.sep}} &= (32 \text{ ft/sec}^2) * 310.3 \text{ Sec} * \ln (4525/1542 + 376) - \\ &\quad 0.9 * 32 \text{ ft/sec}^2 * 123.6 \text{ Sec} \end{aligned}$$

$$\text{Velocity at Booster Separation} = 4,963 \text{ Ft/sec or Mach 4.67}$$

"k" was assumed to be 0.9 after reviewing the flight trajectory until booster separation at 23 miles downrange and 29 miles altitude, and realizing that 90% of this boost energy was spent overcoming gravity.

$$\begin{aligned} \text{Total Velocity Gained by the vehicle after launch:} \\ 22,026 \text{ Ft/sec} + 4,963 \text{ Ft/sec} &= 26,989 \text{ FT/sec} \end{aligned}$$

SUPERTANKER EVALUATION

Using Equation 1) a propulsion analysis of the Supertanker will revealed its propulsion parameters. The velocity gained by the Supertanker after Booster Separation is calculated by the following:

Because the thrust of the SSME's has not changed with the Supertanker Concept, the Thrust-to-Weight after Booster Unit Separation can not change. Therefore, Vehicle Mass after Booster Unit Separation must remain at 1542 Klbs. It has been assumed that the Supertanker is 67 Klbs heavier than the ET, therefore the amount of fuel after Booster Unit Separation must be 67Klb less or 1140 Klb

$$\begin{aligned} \text{Using Eq 1): } V_{\text{meco}} &= (32 \text{ ft/sec}^2) * 453.5 \text{ Sec} * \ln (1542/410) - 0 \\ &= 19,210 \text{ Ft/sec} \end{aligned}$$

"k" was again assumed to be zero as in the STS/SRB equation. The difference between the above result for vehicle gained after Booster Unit Separation and Total Velocity Gained after Launch for STS/SRB is the amount of Velocity Gained the Supertanker Vehicle must acquire during the boost phase.

$$\text{or } 26,989 \text{ Ft/sec} - 19,210 = 7,779 \text{ Ft/sec}$$

Because the Specific Impulse is different for the SSME's and the Booster Unit Engines, the Average Vehicle Isp during the boost phase equation 2) is again used:

$$\begin{aligned} \text{Average Vehicle Isp} &= \\ &= \{ (I_{sp1} * Thrust_1) + (I_{sp2} * Thrust_2) \} / (Thrust_1 + Thrust_2) \end{aligned}$$

$$\begin{aligned} \text{Ave Veh Isp} &= \\ &= \{ (407\text{sec} * 1272\text{Klb}) + (405\text{sec} * 4205\text{Klbs}) \} / (1272\text{Klbs} + 4205\text{Klbs}) \\ &= 406 \text{ Seconds} \end{aligned}$$

$$\begin{aligned} \text{Using Eq 1): } \\ 7,779 \text{ FT/sec} &= (32 \text{ ft/sec}^2) * 406 \text{ Sec} * \ln (GLOW/1,669,537) - \\ &0.8 * 32 \text{ ft/sec}^2 * 122 \text{ Sec} \end{aligned}$$

$$\underline{GLOW} = \underline{3838 \text{ Klbs}}$$

"k" was assumed to be 0.8 because the Booster Unit Separation would take place farther downrange while altitude wouldn't necessary need to change. Therefore it was assumed that less of the vehicles energy was spent overcoming gravity.

SUPERTANK SIZE

GLOW was found in Appendix A as 3,838,000 Lbs. In addition, Vehicle Dry Weight is 535,000 Lbs. The amount of propellant (LH2 and LOX) required is 3,303,500 Lbs. Because the LOX-to-Fuel ratio is 6 : 1, the amount of LH2 and LOX loaded at atmospheric pressure onto the Supertanker is 472 KLbs and 2832 KLbs respectively. If a 3.0% ullage is included, then that amount of fuel would required tanks with a volume capacity of 110,000 Ft³ for LH2 and 40,950 Ft³ for LOX⁽¹³⁾.

LH2 TANK DIAMETER

(Reference Figure 5, LH2 Tank), Because the length of the hydrogen barrel is fixed (at 76 Feet) as well as the size of the domes, the only variable is the tank diameter. This diameter is found by doing the following calculations:

Volume of LH2 tank: Volume of Tank Barrel + Volume of both Domes

Because the domes are not hemispheres, but are elliptical. Their volumes will be calculated by:

EQU 3) $V_{dom} = (4/3 * \pi * a^2 * b)$
 where "a" is major radius of 228 inch or 19.0 Ft (which is the radius of Supertank as derived through iteration) and "b" is minor radius of 172.8 inch or 14.4 Ft (which is the radius of curvature of dome as derived in TANK DOME DIMENSIONING).

Using Equation 3)

Vol of LH2 Domes = 21,775 Ft³ = $(4/3 * \pi * 19^2 * 14.4)$

Volume of Tank Barrel: 110,000 - 21,775 = 88,225 Ft³

Cross area of Tank: Volume / Barrel Length : $\pi * \text{Diameter}^2 / 4$
 = 88,225 Ft³ / 76 Ft = 1160.9 Ft²

Diameter of Tank Barrel: 38.2 FT = $\{1160.9 \text{ Ft}^2 * (4/\pi)\}^{0.5}$

TANK DOME DIMENSIONING

The aft fuel dome was designed using a 211.855 inch radius of curvature⁽⁵⁾. Therefore, its radius is 1.28 times greater than the tanks barrels 165 inch (13.75 Foot) radius. If a Supertanker with a 19.0 foot (228 inch) radius tank was used, then the radius of curvature would be 292.8 inch. $[(228 / 165) * 211.855 \text{ inch}]$
 From Figure 6, it can be found that the radius of curvature is 1.70 $[211.855 / 124.125]$ times greater than the longitudinal distance of dome ellipse to dome/barrel interface on todays External Tank. Hence, this distance on the SUPERTANKER would be 172 inch (14.4 feet). This dimension is found by 292.8 inch / 1.70. Therefore, the longitudinal distance has been increased by 47.9 inch or 4.0 feet for each dome.

LOX TANK DIMENSIONING

(Reference Figure 5, LOX Tank), The LOX Tank diameter and size of aft dome is determined by the diameter of the LH2 Tank, as found above. The only variable that can be changed due to fuel volume requirements on the LOX Tank is the major axis found using equation 3. The minor axis will initially assumed to be the radius of the tank

The major axis is found by doing the following calculations:

$$\begin{aligned}\text{Volume of LOX tank: Volume of Aft Dome + Volume of Frwrld Ogive} \\ 40,950 \text{ Ft}^3 &= (21,775 \text{ Ft}^3) / 2 + 4/3 * \pi * a^2 * 19.0 \text{ Ft} \\ a &= 19.4 \text{ Ft}\end{aligned}$$

Length of LOX Tank is then found as:

Length of Aft Dome + Length of Forward Ogive + Length of Nose Cone

$$\text{Length of Lox Tank} = 14.4 \text{ Ft} + 19.4 \text{ Ft} + 3.65 \text{ Ft} = \underline{37.5 \text{ FT}}$$

$$\begin{aligned}\text{Total Length of LH2 Tank} &= \text{Length of both domes} + \text{Length of Barrel} \\ &= (14.4 * 2) \text{ Ft} + 76 \text{ Ft} = \underline{104.8 \text{ Ft}}\end{aligned}$$

$$\begin{aligned}\text{Total Length of Supertank} &= \text{Length of LH2 Tank} + \text{Length of LOX Tank} \\ &\quad + \text{Length of LOX Nose Cone} \\ &= 104.8 \text{ Ft} + 37.5 \text{ Ft} + 3.65 \text{ Ft} \\ &= \underline{145.9 \text{ Ft}}\end{aligned}$$

APPENDIX C

LH2 BOOSTER UNIT FEEDLINE SIZE

LIFTOFF THRUST = 5538 KLBS (4149 from B.U. & 1153 from SSME's)
Booster Unit Thrust = 4385 KLBS
SUPERTANKER Isp = 382 SECONDS
FUEL RATIO (O/F) = 6:1

BOOSTER LH2 FLOW RATE = 1,640 LBS/SEC $[(4,385,592 / 382) * (1/7)]$
372.7 FT³/SEC $[(1640 \text{ LBS/SEC}) / (4.4 \text{ LB/FT}^3)]$

SSME THRUST * 3 = 1,480,000 LBS
SSME Isp = 453.5 SECONDS
SSME FUEL RATIO = 6:1
LH2 FLOW RATE = 466 LBS/SEC $[(1,480,000 / 453.5) * (1/7)]$
106 FT³/SEC $[(466 \text{ LBS/SEC}) / (4.4 \text{ LBS/FT}^3)]$

ET LH2 FUEL LINE = 17 INCH DIAMETER = 1.58 FT² CROSS AREA
LH2 FUEL LINE VELOCITY = 67.1 FT/SEC (106 / 1.58)

AREA OF SUPERTANKER LH2 FEEDLINE = 5.55 FT² = 800 INCH²
 $(372.7 \text{ FT}^3/\text{SEC}) / (67.1 \text{ FT/SEC})$
DIAMETER OF LH2 FEEDLINE = 31.9 INCH $[(800 * (4/\pi))^{\wedge}0.5]$

LOX FEEDLINE SIZE

NOMINAL THRUST = 5538 KLBS (4385 from B.U. & 1153 from SSME's)
SUPERTANKER Isp = 410.6 SECONDS
FUEL RATIO (O/F) = 6:1
LOX FLOW RATE = 11,561 LBS/SEC $[(5,538,000 / 410.6) * (6/7)]$
163 FT³/SEC $[(11561 \text{ LBS/SEC}) / (71 \text{ LBS/FT}^3)]$

F-1 THRUST = 1,500,000 LBS
F-1 Isp = 260 SECONDS
F-1 FUEL RATIO = 2.27:1
LOX FLOW RATE = 4005 LBS/SEC $[(1,500,000 / 260) * (2.27/3.27)]$
56.4 FT³/SEC $[(4005 \text{ LBS/SEC}) / (71 \text{ LBS/FT}^3)]$

F-1 LOX FUEL LINE = 17 INCH DIAMETER = 1.58 FT² CROSS AREA
LOX FUEL LINE VELOCITY = 35.7 FT/SEC (56.4 / 1.58)

AREA OF SUPERTANKER LOX FEEDLINE = 4.56 FT² = 656 INCH²
 $[(163 \text{ FT}^3/\text{SEC}) / (35.7 \text{ FT/SEC})]$
DIAMETER OF LOX FEEDLINE = 28.9 INCH $[(656 * (4/\pi))^{\wedge}0.5]$

APPENDIX D

PROPELLANT COST (9)

Liquid Hydrogen - \$ 1.18 per pound
Liquid Oxygen - \$ 0.04 per pound
Solid Propellant - \$10.00 per pound

SRB-STS (6)

LH2 -	227,161 Lbs	*	\$ 1.18/lb	=	\$	268,050
LOX -	1,362,967 Lbs	*	\$ 0.04/lb	=	\$	54,519
SRB -	2,208,000 Lbs	*	\$10.00/lb	=	\$	22,080,000

Total Cost of Propellant					=	\$ 22,402,569

This amounts to 4% of the total recurring cost for SRB-STS.

SUPERTANKER

LH2 -	472,000 Lbs	*	\$ 1.18/lb	=	\$	556,960
LOX -	2,832,000 Lbs	*	\$ 0.04/lb	=	\$	113,280

Total Cost of Propellant					=	\$ 670,240

This would amount to 0.12% of the total recurring cost for SRB-STS.

COMBINE CYCLE

LH2 -	282,900 Lbs	*	\$ 1.18/lb	=	\$	333,822
LOX -	796,600 Lbs	*	\$ 0.03/lb	=	\$	23,900

Total Cost of Propellant					=	\$ 357,720

DELTA CLASS SUPERTANKER APPLICATION

<u>DELTA CLASS</u>		<u>SHUTTLE CLASS</u>
1,520 lbs	Payload shoud or Orbiter	220,092 lbs
7,600 lbs	Payload	70,000 lbs
6,200 lbs	Supertank	120,300 lbs
3,500 lbs	Booster Unit (Structure)	73,004 lbs
3,900 lbs	Booster Unit (engines)	54,533 lbs
<hr/>		
22,720 lbs	Total Vehicle Inert Weight @ Launch	537,929 lbs
18,145 lbs	Mass at MECO	410,392 lbs
Ave Isp for Booster Engines (Boost Phase)		404.5 sec
Isp Vacuum		427.0 sec
Relative Velocity at Booster Unit Separation		7,779 Ft/sec
Velocity Changed after Booster Unit Sep		19,210 Ft/sec

Values for mass of Delta Class vehicle was arrived by scaling the Shuttle Class Vehicle down to reflect the Mass to Orbit for the Delta Class. Two thirds of B.U. Engine mass, half of B.U. Structure mass, and the Payload shroud is jettisoned at Booster Unit Separation.

Using Equation 1) a propulsion analysis of the Delta Class Supertanker will revealed its propulsion parameters. The velocity gained by the Supertanker after Booster Unit Separation as well as the velocity at Booster Unit Separation is assumed to remain the same as the Shuttle-Supertanker.

Using Eq 1) to find Mass at Booster Unit Separation (Msep):

$$19,210 \text{ Ft/sec} = (32 \text{ ft/sec}^2) * 427 \text{ Sec} * \ln (Msep/18,145) - 0$$

$$= 68,730 \text{ lbs}$$

"k" was again assumed to be zero as in the Supertanker equation.

Using Eq 1) to find GLOW for the Delta Class Vehicle:

$$7,779 \text{ FT/sec} = (32 \text{ ft/sec}^2) * 404.5 \text{ Sec} * \ln (GLOW/74,580) - 0.8 * 32 \text{ ft/sec}^2 * 122 \text{ Sec}$$
GLOW = 173,177 lbs

SUPERTANK SIZE

The amount of propellant (LH2 and LOX) required is 150,450 Lbs. Because the LOX-to-Fuel ratio is 6 : 1, the amount of LH2 and LOX loaded at atmospheric pressure onto the Supertanker is 21,500 Lbs and 128,950 Lbs respectively. If a 3.0% ullage is included, then that amount of fuel would required tanks with a volume capacity of 5,250 Ft^3 for LH2 and 1,870 Ft^3 for LOX'''.

TANK DIMENSIONS

If a 10 Foot diameter core vehicle is used then calculations as performed in Appendix A will yield a LH2 tank length of 72.9 Feet. And a LOX tank with the same shape as the LH2 tank will yield a length of 26.0 Feet.

TITAN CLASS SUPERTANKER APPLICATION

<u>TITAN CLASS</u>		<u>SHUTTLE CLASS</u>
8,500 lbs	Payload shroud or Orbiter	220,092 lbs
42,900 lbs	Payload	70,000 lbs
36,500 lbs	Supertank	120,300 lbs
18,000 lbs	Booster Unit (Structure)	73,004 lbs
24,000 lbs	Booster Unit (Engines)	54,533 lbs

129,900 lbs	Total Vehicle Inert Weight @ Launch	537,929 lbs
96,400 lbs	Mass at MECO	410,392 lbs
Ave Isp for Booster Engines (Boost Phase)		404.5 sec
Isp Vacuum		427.0 sec
Relative Velocity at Booster Unit Separation		7,779 Ft/sec
Velocity Changed after Booster Unit Sep		19,210 Ft/sec

Values for mass of Titan Class vehicle was arrived by scaling the Shuttle Class Vehicle down to reflect the Mass to Orbit for the Titan Class. Two thirds of B.U. Engine mass, half of B.U. Structure mass, and the Payload shroud is jettisoned at Booster Unit Separation.

Using Equation 1) a propulsion analysis of the Titan Class Supertanker will revealed its propulsion parameters. The velocity gained by the Supertanker after Booster Unit Separation as well as the velocity at Booster Unit Separation is assumed to remain the same as the Shuttle-Supertanker.

Using Eq 1) to find Mass at Booster Unit Separation (Msep):

$$19,210 \text{ Ft/sec} = (32 \text{ ft/sec}^2) * 427 \text{ Sec} * \ln (Msep/96,400) - 0$$

$$= 393,220 \text{ lbs}$$

"k" was again assumed to be zero as in the Supertanker equation.

Using Eq 1) to find GLOW for the Titan Class Vehicle:

$$7,779 \text{ FT/sec} = (32 \text{ ft/sec}^2) * 404.5 \text{ Sec} * \ln (GLOW/426,720) - 0.8 * 32 \text{ ft/sec}^2 * 122 \text{ Sec}$$

GLOW = 990,833 lbs

SUPERTANK SIZE

The amount of propellant (LH2 and LOX) required is 894,500 Lbs. Because the LOX-to-Fuel ratio is 6 : 1, the amount of LH2 and LOX loaded at atmospheric pressure onto the Supertanker is 127,750 Lbs and 766,750 Lbs respectively. If a 3.0% ullage is included, then that amount of fuel would required tanks with a volume capacity of 31,200 Ft³ for LH2 and 11,100 Ft³ for LOX.

TANK DIMENSIONS

If a vehicle length of 111.5 Foot is used with 16.5 feet allotted for engines and propulsion system, then calculations as performed in Appendix A will yield a vehicle diameter of 24.9 Feet.

SHUTTLE-Z CLASS SUPERTANKER APPLICATION

<u>SHUTTLE-Z CLASS</u>		<u>SHUTTLE CLASS</u>
90,000 lbs	Payload shroud or Orbiter	220,092 lbs
450,000 lbs	Payload	70,000 lbs
383,000 lbs	Supertank	120,300 lbs
216,000 lbs	Booster Unit (Structure)	73,004 lbs
251,800 lbs	Booster Unit (Engines)	54,533 lbs
<hr/>		
1,390,800 lbs	Total Vehicle Inert Weight @ Launch	537,929 lbs
<hr/>		
1,024,900 lbs	Mass at MECO	410,392 lbs
Ave Isp for Booster Engines (Boost Phase)		404.5 sec
Isp Vacuum		427.0 sec
Relative Velocity at Booster Unit Separation		7,779 Ft/sec
Velocity Changed after Booster Unit Sep		19,210 Ft/sec

Values for mass of Shuttle-Z Class vehicle was arrived by scaling the Shuttle Class Vehicle down to reflect the Mass to Orbit for the Shuttle-Z Class. Two thirds of B.U. Engine mass, half of B.U. Structure mass, and the Payload shroud is jettisoned at Booster Unit Separation.

Using Equation 1) a propulsion analysis of the Shuttle-Z Class Supertanker will revealed its propulsion parameters. The velocity gained by the Supertanker after Booster Unit Separation as well as the velocity at Booster Unit Separation is assumed to remain the same as the Shuttle-Supertanker.

Using Eq 1) to find Mass at Booster Unit Separation (Msep):

$$19,210 \text{ Ft/sec} = (32 \text{ ft/sec}^2) * 427 \text{ Sec} * \ln (Msep/1,024,900) - 0$$

$$= 4,180,600 \text{ lbs}$$

"k" was again assumed to be zero as in the Supertanker equation.

Using Eq 1) to find GLOW for the Shuttle-Z Class Vehicle:

$$7,779 \text{ FT/sec} = (32 \text{ ft/sec}^2) * 404.5 \text{ Sec} * \ln (GLOW/4,546,500) - 0.8 * 32 \text{ ft/sec}^2 * 122 \text{ Sec}$$

$$\underline{GLOW = 10,556,950 \text{ lbs}}$$

SUPERTANK SIZE

The amount of propellant (LH2 and LOX) required is 9,166,150 Lbs. Because the LOX-to-Fuel ratio is 6 : 1, the amount of LH2 and LOX loaded at atmospheric pressure onto the Supertanker is 1,309,450 Lbs and 7,856,700 Lbs respectively. If a 3.0% ullage is included, then that amount of fuel would required tanks with a volume capacity of 319,400 Ft³ for LH2 and 114,000 Ft³ for LOX.

TANK DIMENSIONS

If a 60 Foot diameter core vehicle is used then calculations as performed in Appendix A will yield a LH2 tank length of 123 Feet. And a LOX tank with the same shape as the LH2 tank will yield a length of 44.0 Feet.

APPENDIX F

COMBINED CYCLE PERFORMANCE EVALUATION

<u>VELOCITY RANGE</u>	<u>FUEL CONSUMED (KLBS)</u>	<u>INITIAL MASS</u>	<u>Isp (SEC)</u>	<u>FLIGHT TIME</u>
0 TO 1 MACH	55 (27.5 LH2, 27.5 LOX)	1495 KLBS	1600	25.4
1 TO 2 MACH	38 (29.2 LH2, 8.8 LOX)	1440 KLBS	2200	24.7
2 TO 3 MACH	26 (23.2 LH2, 2.3 LOX)	1402 KLBS	3200	24.3
3 TO 4 MACH	23 (23.0 LH2, 0.0 LOX)	1377 KLBS	3500	23.8
4 TO 5 MACH	24 (24.0 LH2, 0.0 LOX)	1354 KLBS	3200	23.5
5 TO 6 MACH	30 (30.0 LH2, 0.0 LOX)	1330 KLBS	2600	22.9
	STAGE 80 KLBS			
6 TO 26 MACH	885 (126 LH2, 758 LOX)	1200 KLBS	440	294
	MASS AT MECO	335 KLBS		

TOTAL TIME to MECO 438.6 Sec = 7.3 Minutes

TOTAL BOOSTER FUEL 156.9 LH2 AND 38.6 LOX

TOTAL SHUTTLE FUEL 282.9 LH2 AND 796.6 LOX = 1079.5 KLBS

The following is a breakdown of the GLOW of 1495 Klbs:

Mass at MECO	=	335 Klbs
Mass of External Tank is assumed to remain at		69 Klbs
Mass after Booster Separation	=	1200 Klbs
Mass of Booster Unit & Air Breather	=	105 Klbs
Fuel for Air Breather (LH2)	=	196 Klbs
Mass of Booster Unit Engines (5)	=	25 Klbs

APPENDIX G(13)

LH2 HEAT FLUX REQUIREMENTS

As found in the 1989 Fundamentals

Pressure = 20 psia Volume vapor = 8.95 Ft³/lbm
Temperature = 39 Rankine Density Liq = 4.32 lbm/Ft³
Delta Enthalpy (across dome) = 311 - 122 = 189 BTU/lbm

Maximum drainage from tanks occurs during boost phase. As found in Appendix A:

Maximum Thrust / Isp = (4205 + 1296 Klbs) / (408 Sec)
= 13,488 lbs/sec

Since LH2 mass flow is 1/7 of this total, then:

LH2 Mass Flow: 1,887 lbs/sec = 437 FT³/sec
[1,887 lbs/sec / 4.32 lbm/FT³]

which is the same amount of gaseous Hydrogen at 20 psia that must be generated.

This amount of GH2 (in mass) is then:

GH2 Mass Gen: 48.8 lbm/sec = [437 FT³/sec / 8.95 Ft³/lbm]

Finally, to generate this amount of GH2 would require:

9,224 BTU/sec = 33.2 10⁶ BTU/hr = 9,730 Kilowatts
from the calculation: [(48.8 lbm/sec) * (189 BTU/lbm)]

LOX HEAT FLUX REQUIREMENTS

As found in the 1989 Fundamentals

Pressure = 20 psia Volume vapor = 2.67 Ft³/lbm
Temperature = 168 Rankine Density Liq = 70.2 lbm/Ft³
Delta Enthalpy (across dome) = 35.1 - (-55.1) = 90.2 BTU/lbm

Again Maximum drainage from tanks is calculated to be 13,208 lb/sec. LOX to LH2 ratio is 6:1 therefore:

LOX Mass Flow: 11,322 lbs/sec = [11,322 lbs/sec / 70.2lbm/ft³]
= 161.3 FT³/sec

which is the same amount of gaseous Oxygen at 20 psia that must be generated.

GOX Mass Gen: 60.4 lbm/sec = [161.3 FT³/sec / 2.67 Ft³/lbm]

Finally, to generate this amount of GOX would require:

5,450 BTU/sec = 19.6 10⁶ BTU/hr = 5,750 Kilowatts
from the calculation: [(60.4 lbm/sec) * (90.2 BTU/lbm)]

about the author

Douglas G. Thorpe

- * received B.S. in Engineering Physics from Eastern Kentucky Univ. in 1985.
- * working towards receiving M.S. in Thermal-Fluids from the Mechanical Eng Dept at the University of Central Florida.
- * was a part-time member of the Lockheed Advance Programs Group during the Liquid Rocket Booster Integration Accessment on Facility Impacts at NASA Kennedy Space Center during 1988.
- * has been employed as a Mechanical Systems Engineer for External Tank Program for Lockheed Space Operations Company since Aug 1987.

Questions and comments can be made through the following address:

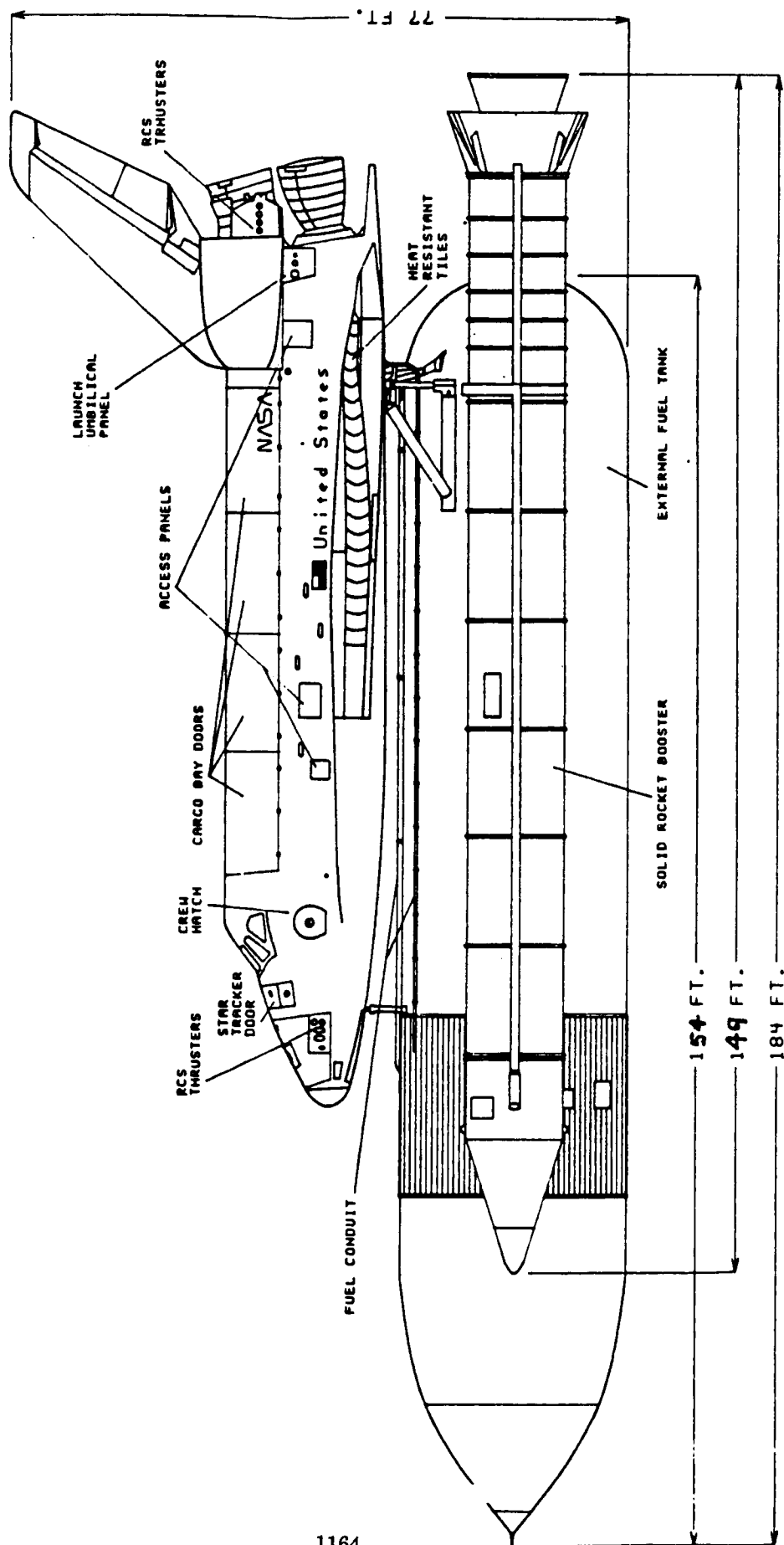
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REFERENCE FIGURE

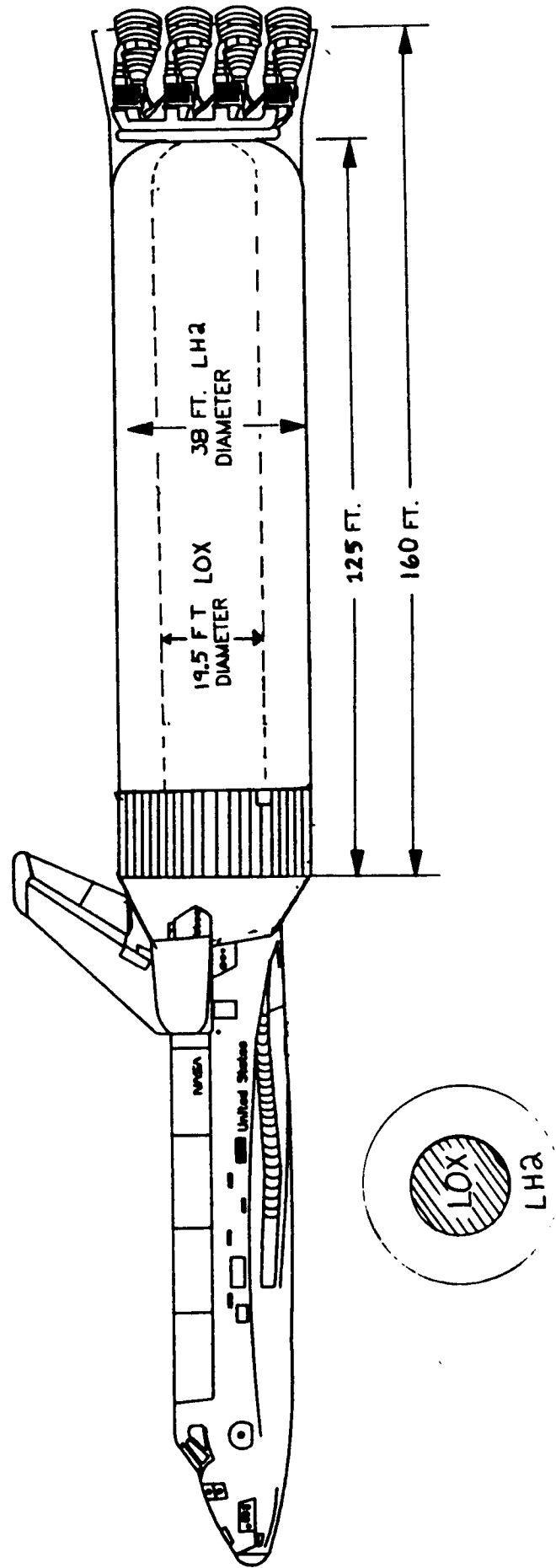


MEMORANDUM



FIGURE 3

SUPER-TANKER II SPACE SHUTTLE



PAGE 1 OF 2

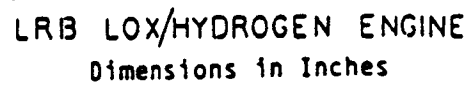


FIGURE 4

EXPENDABLE LOX/H₂ GAS GENERATOR ENGINE CHARACTERISTICS

GENERAL DYNAMICS
Space Systems Division

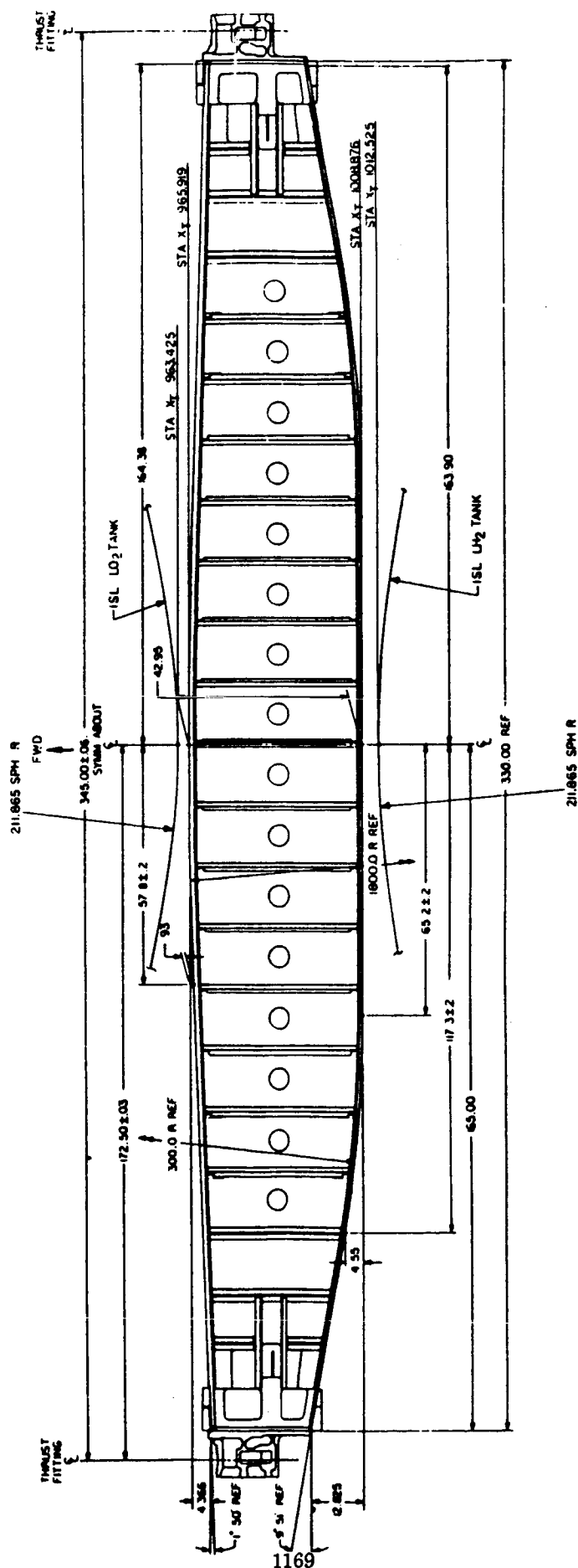
PAGE 2 OF 2

LRB

Engine Parameters	Nominal Thrust	Minimum Thrust
Throttle, (percent)	100	75.0
Vacuum Thrust (lb)	558,000	418,500
Sea Level Thrust (lb)	518,574	388,930
Chamber Pressure (psia)	2250	1701
Vacuum Isp (sec delivered)	411.4	412.3
Sea Level Isp (sec)	382.3	373.2
Mixture Ratio	6.0	6.0
Oxidizer Flow Rate (lb/sec)	1162.7	893.3
Fuel Flow Rate (lb/sec)	193.8	148.9
Nozzle Area Ratio	20	
Throat Radius (in)	6.54	
Exit Diameter (in)	58.4	
Overall Length (in)	112.9	
Inlet Pressure: LOX (psia)	65	
Inlet Pressure: LH ₂ (psia)	45	
Inlet Temperature	Saturation at 16 psia	
Mission Life	1	
No. of Starts	5	
Reliability	99% @ 90% confidence level	
Dry Weight (lb)	6100	

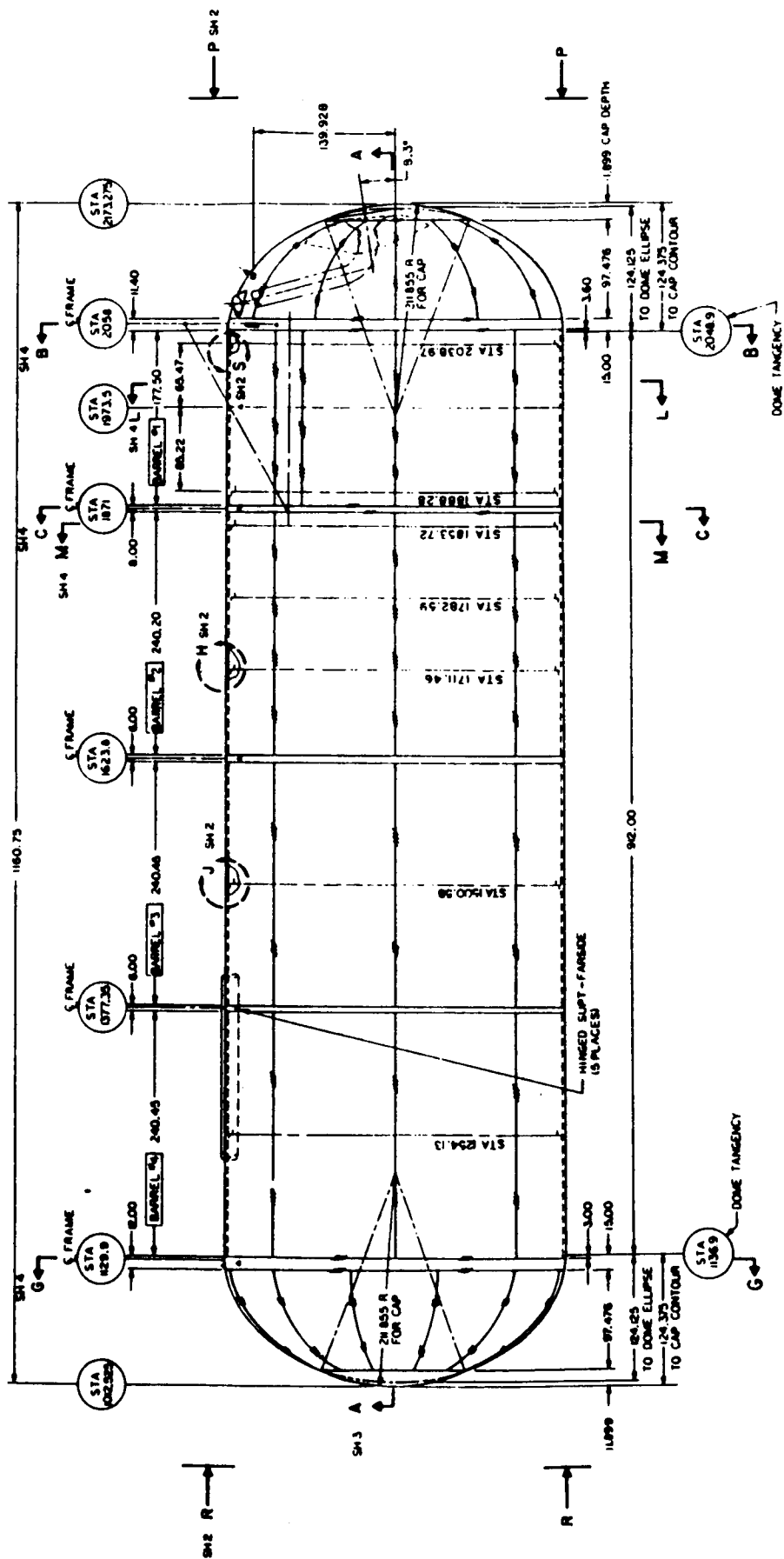
USRB TRUST BEEM

PAGE 1 OF 3



Y Z A T Z W G O R A J I A D I G J

PAGE 2 OF 3



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Technical drawing of the LO₂ TANK ASSY, showing top, side, and front views with dimensions and labels.

Top View (Left):

- 17.00 DIA LO₂ SUCT'ION FITTING
- 36.00 DIA MANHOLE
- 30° TYP
- 15°
- 20°
- 42.00
- 30.482
- 33.0 O.D.
- 140.0 DIA
- 140°
- SH 2 B
- DOME CAP
- VORTEX BAFFLE

Side View (Center):

- X1-583.425
- X1-843.000
- X1-742.350
- X1-536.740
- X1-371.000
- X1-373.000
- X1-322.250
- X1-340.000
- 6.00
- 6.00
- 3.08
- 104.25
- 104.375
- TO DOME ELLIPSE
- TO CAP CONT'NR
- DOME GORE (2 PCS)
- AST OGIVE GORE (2 PCS)
- BARREL (4 PCS)
- LO₂ TANK ASSY

Front View (Right):

- 30° TYP
- 15°
- 30°
- 45° TYP
- 51°
- SH 3
- CABLE TRAY
- NOSE CAP
- LIGHTNING ROD
- SH 4
- FORWARD OGIVE GORE (18 PCS)

Other Labels:

- SEE VIEW E SH 4 FOR LOCATION OF ELECT JUNK

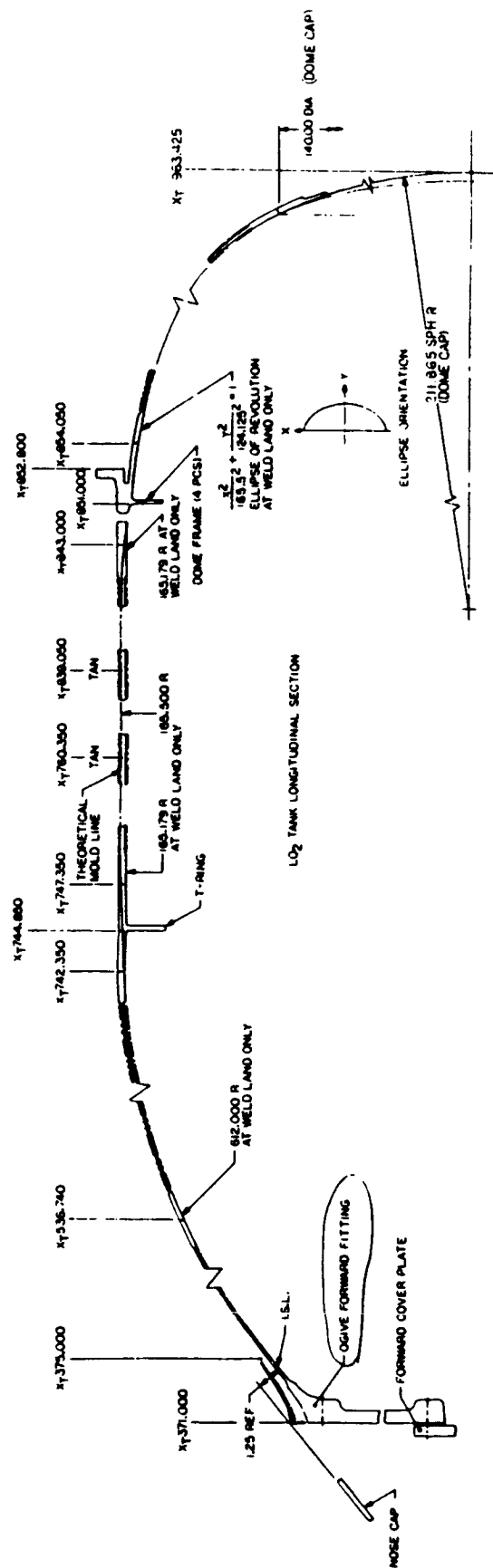


FIGURE 6

ASSESSMENT OF S₁AS CONFIGURATIONS

PRESENTATION
by BOEING

KSC

SEPT 17, 1987

PAGE 1 OF 2

PROPELLANT SAFETY, PERFORMANCE AND COST DATA

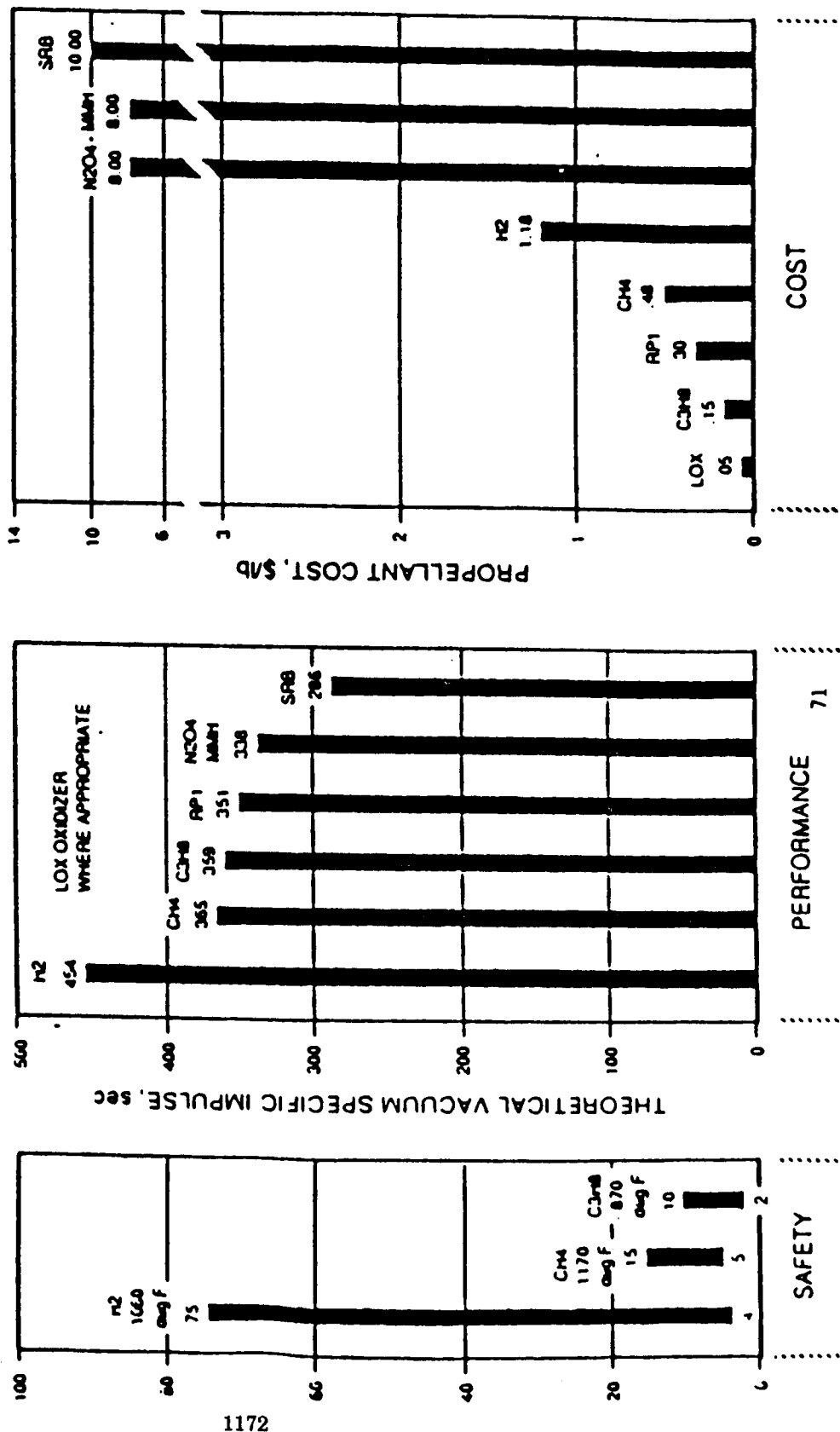


FIGURE 6

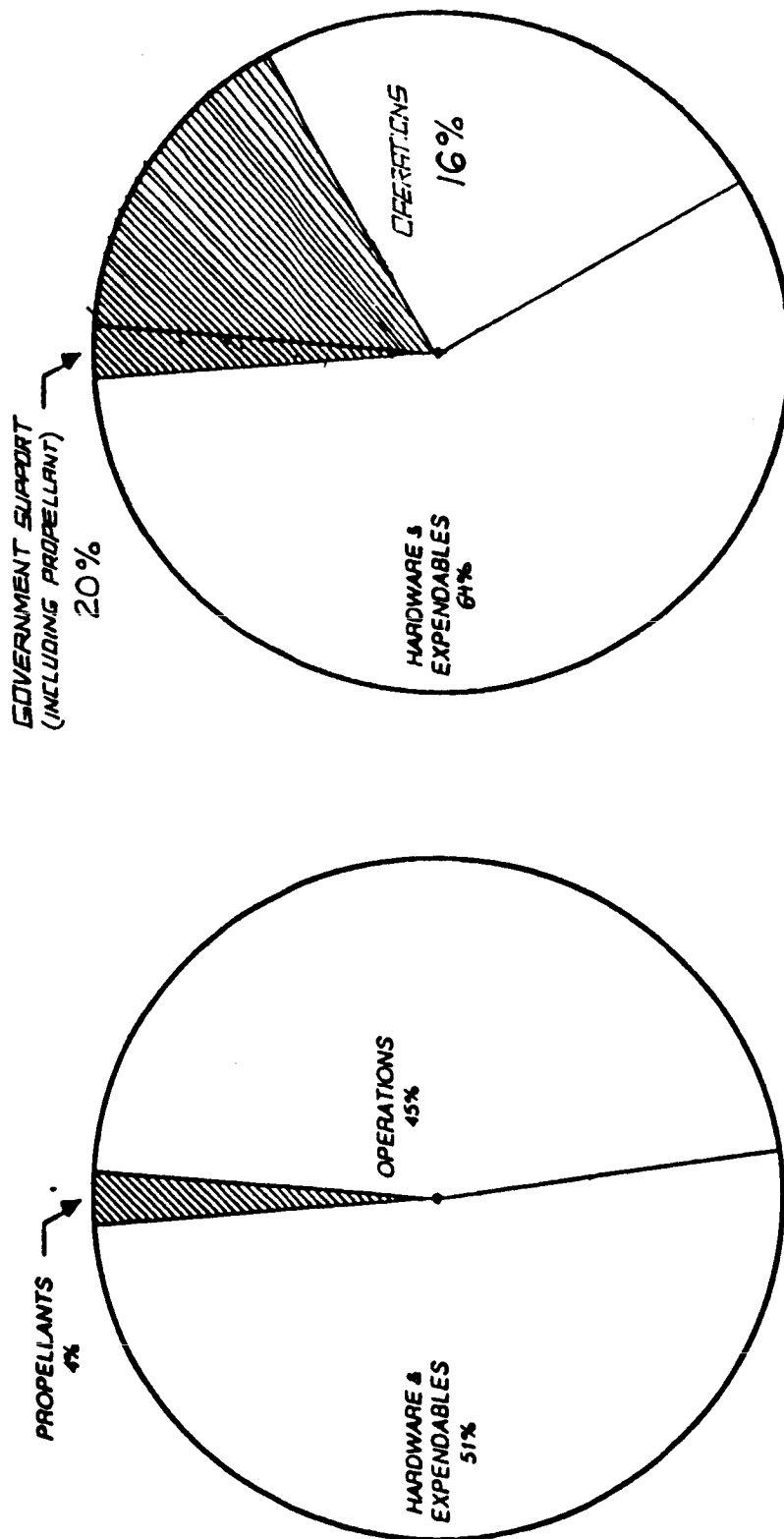
PRESENTED AT
KSC
SEPT 17, 1987

PAGE 2 OF 2

ASSESSMENT OF STAS CONFIGURATIONS

PRESENTATION
by BOEING

RECURRING COST CONSIDERATIONS



SHUTTLE STS

\$273,500,000 PER FLIGHT
\$5,470 PER POUND

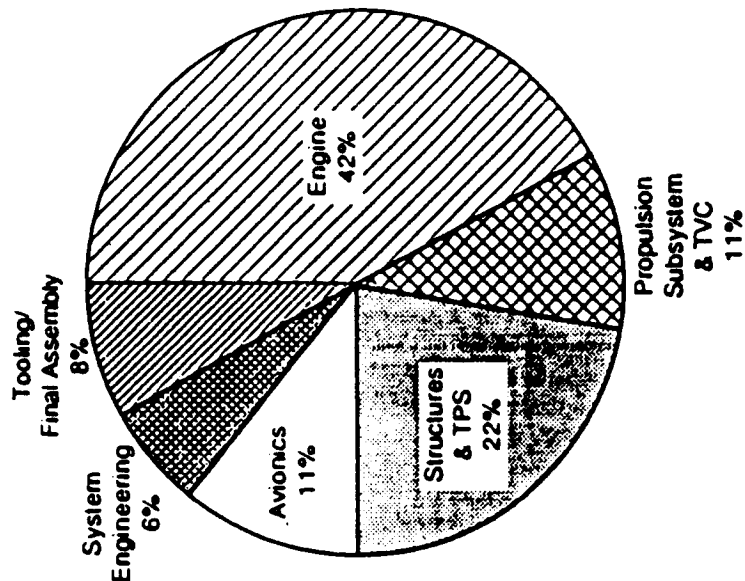
TITAN IV

\$130,000,000 PER FLIGHT
\$3,333 PER POUND

ENGINES ARE MAJOR COST CONTRIBUTOR

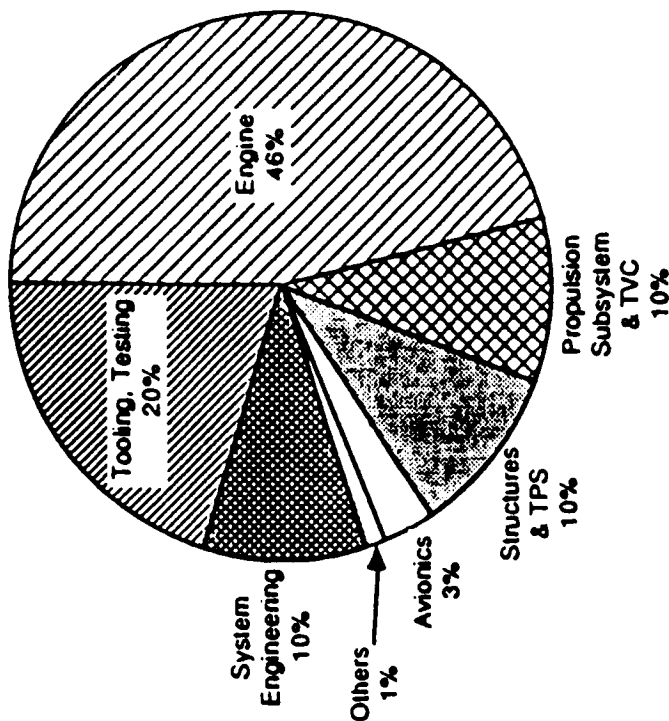
0000 LRB

LO2/LH2 LRB COST BREAKDOWN



AVERAGE UNIT COST = \$51M*

(244 BOOSTERS)



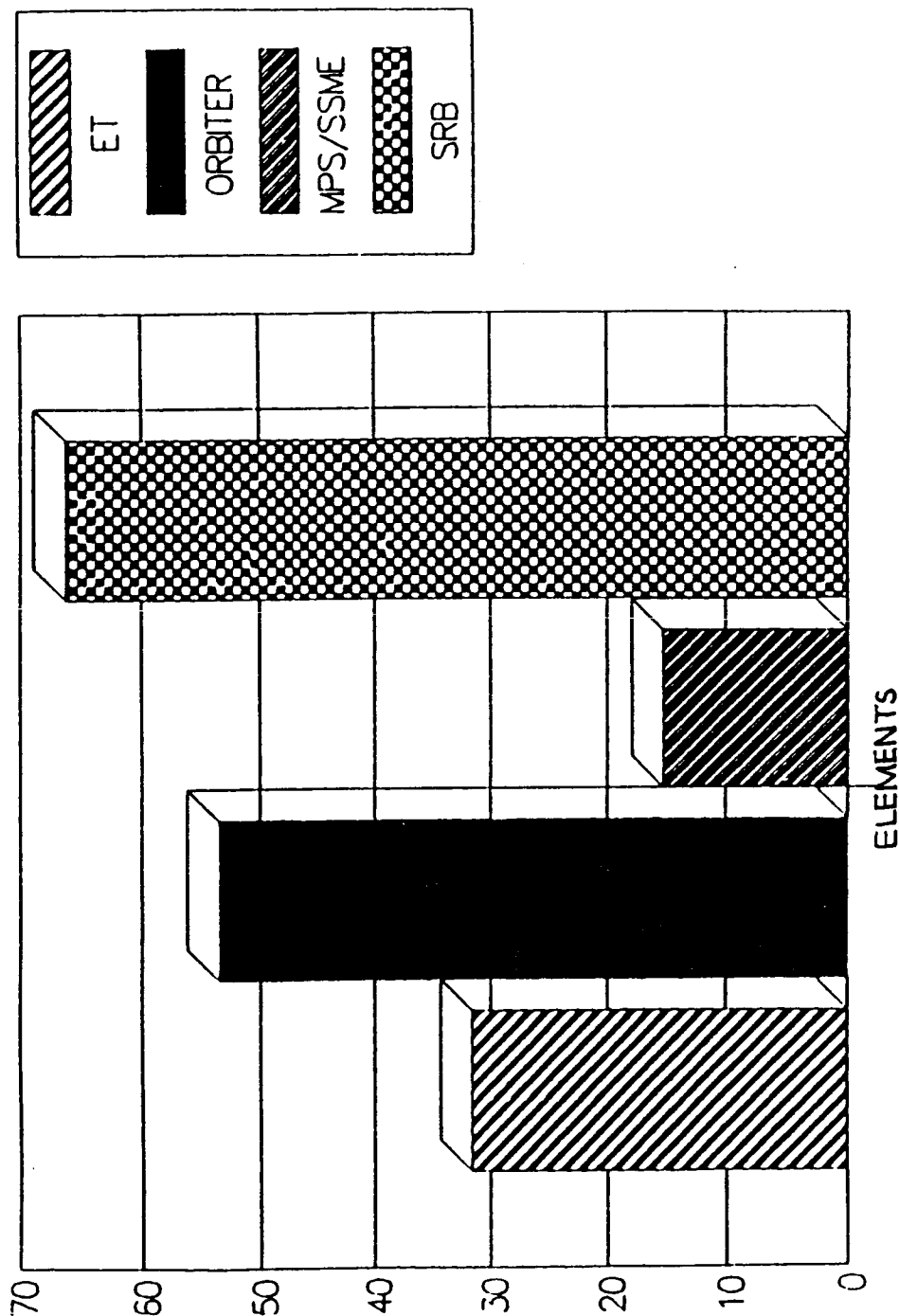
VEHICLE DDT&E = \$ 3,224 M*

* INCLUDE 40% NASA FACTOR

FIGURE 7

HARDWARE COST PER FLIGHT

PAGE 2 OF 2



COST, \$ MILLION

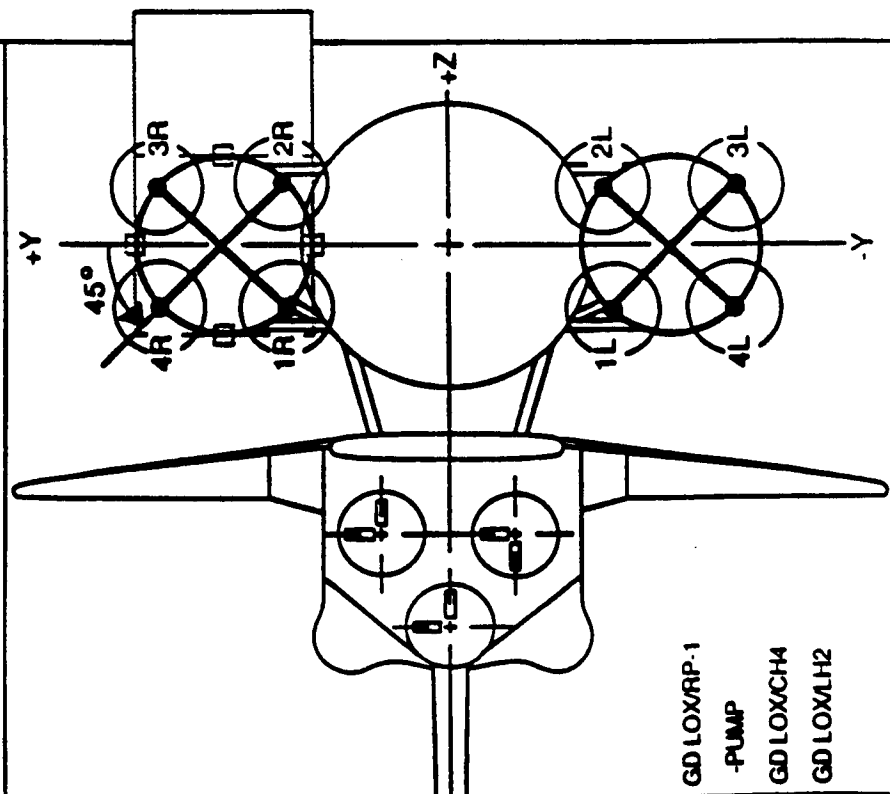
FIGURE 8

LRB PROPOSED ENGINE PROPORTIONS (VIEWS LOOKING FORWARD)

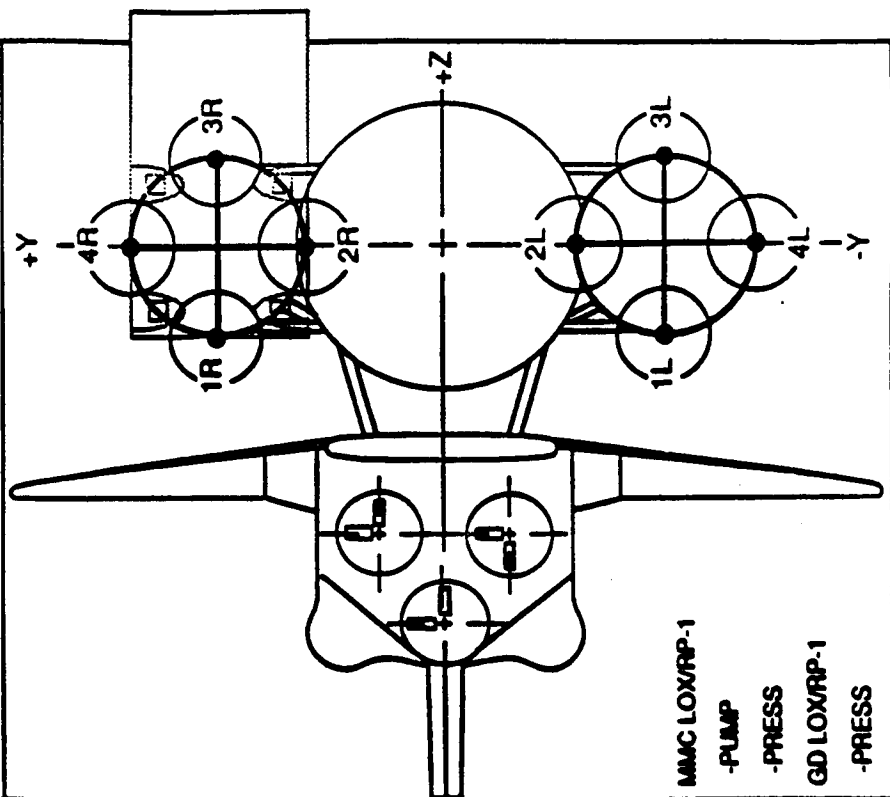
OCT 88



"X" PATTERN

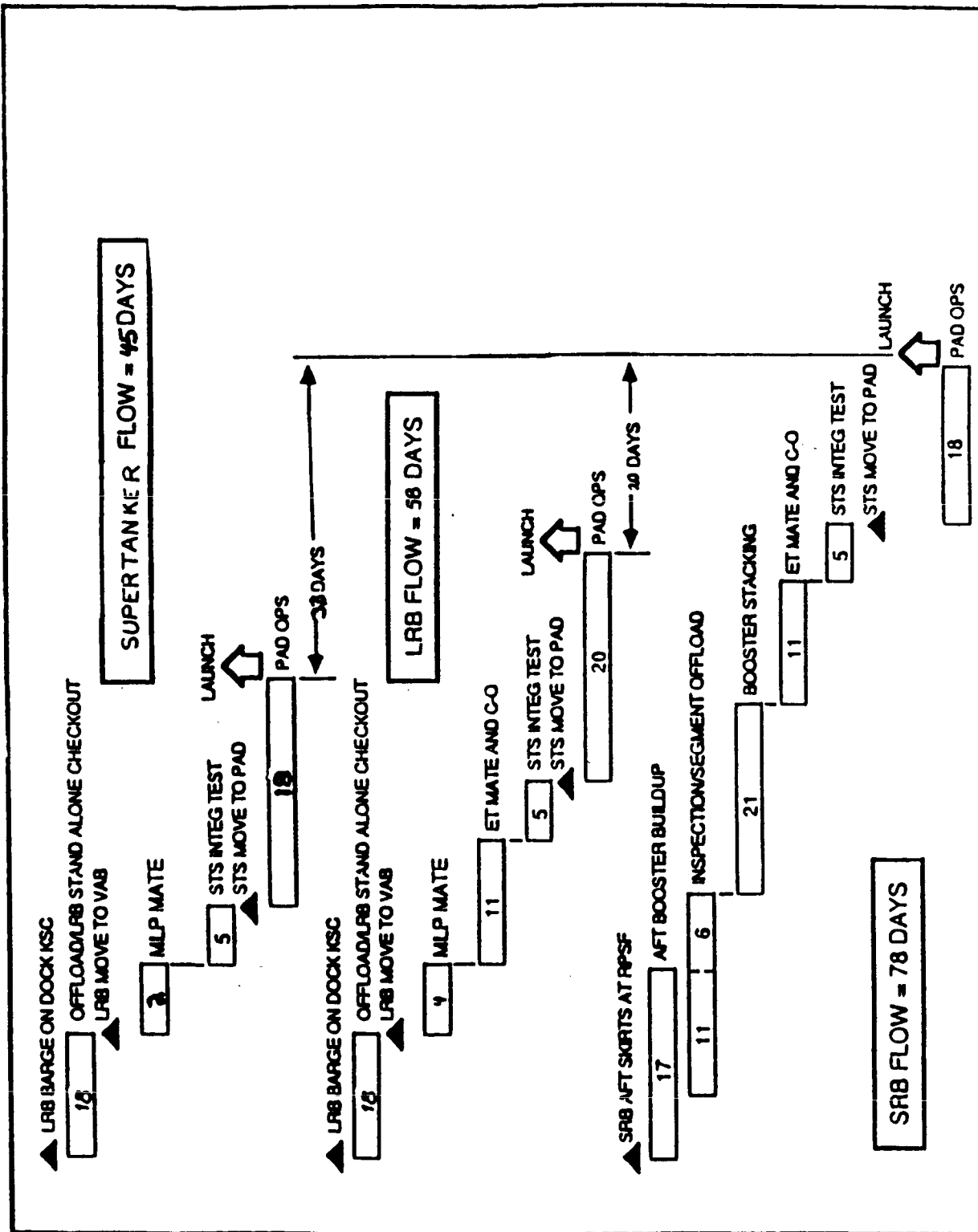


"+" PATTERN



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Space Operations Company

FIGURE 9



NOTE: SRB RETRIEVAL, DISASSEMBLY, REFURBISHMENT AND REMANUFACTURING ARE NOT SHOWN.

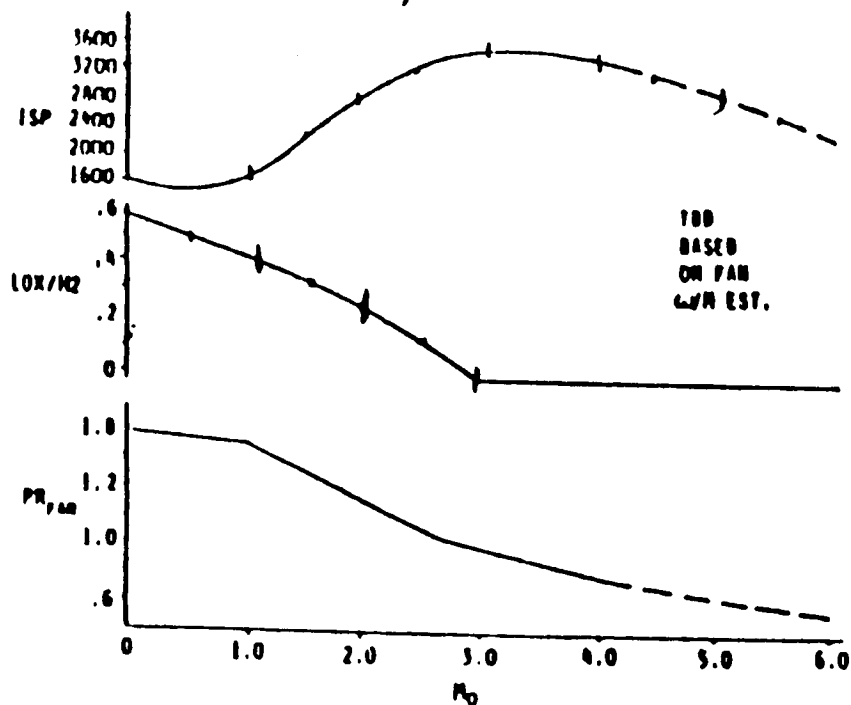
AIAA-87-2000**Rocket Fan—A Hybrid Air-Breathing,
Hydrogen-Fueled Engine**W.B. Kerr and J. Marra, Pratt & Whitney,
West Palm Beach, FL

FIGURE 4.- TYPICAL RF OPERATION

**AIAA/SAE/ASME/ASEE 23rd Joint
Propulsion Conference**

June 29-July 2, 1987/San Diego, California

FIGURE 10

COMBINED CYCLE, ROCKET ENGINE AFTERBURNING

PAGE 2 OF 2

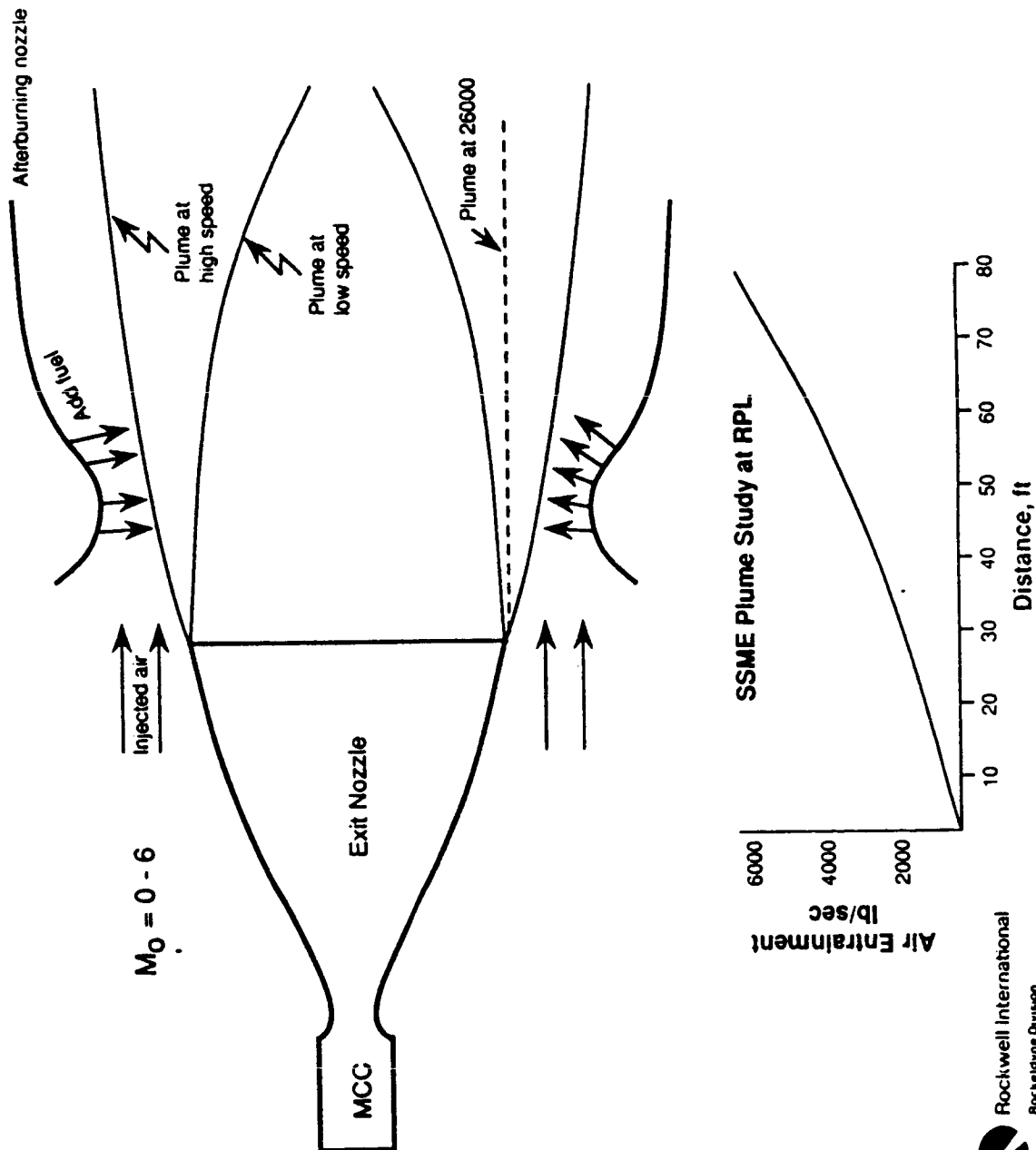


FIGURE 11

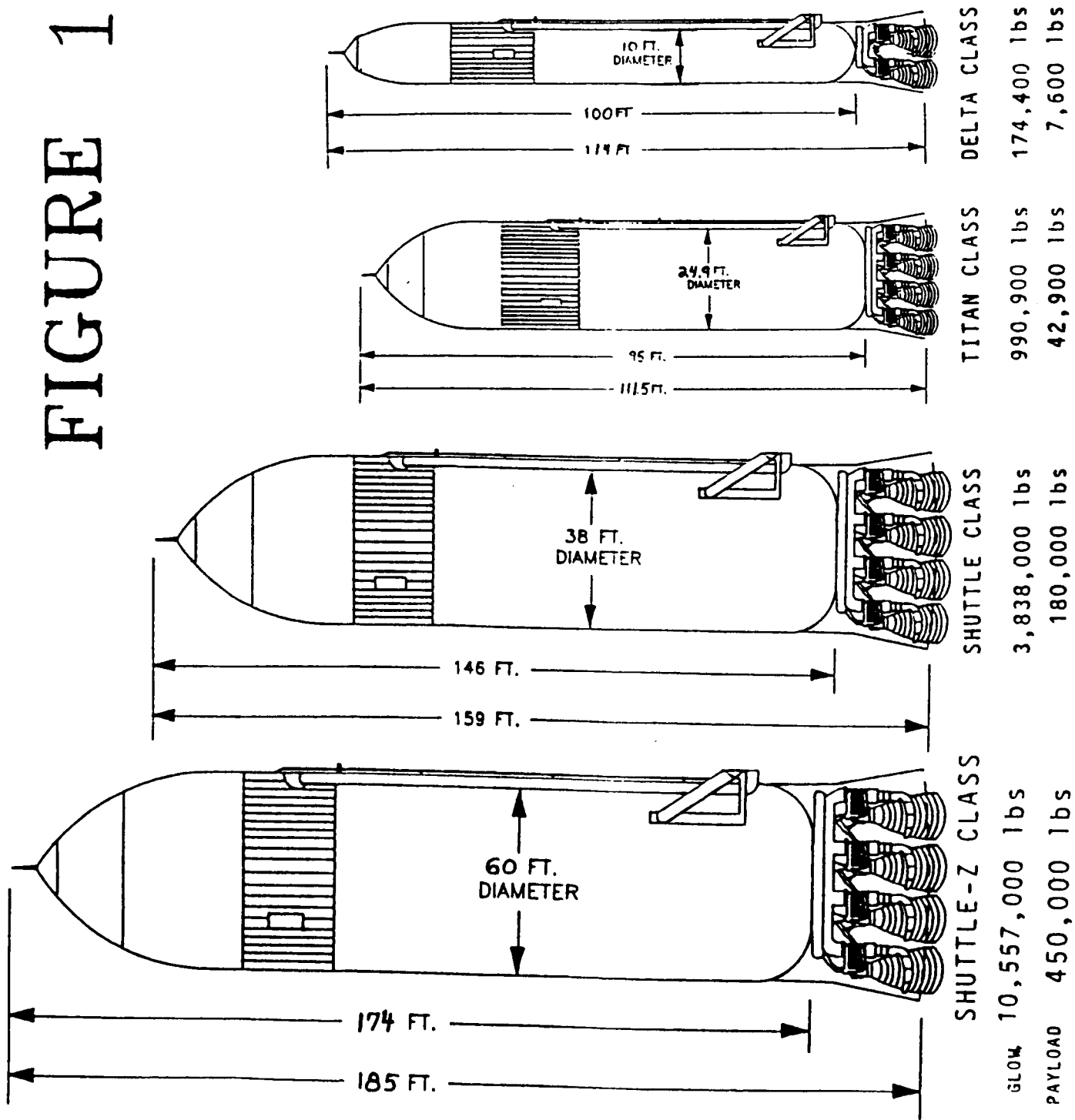




TABLE 1

LIQUID ROCKET BOOSTER INTEGRATION FIRST PROGRESS REVIEW

JULY 1988

TASK 1 - SRB BASELINE DEFINITION

SRB PROCESSING MHRS AND COST (PER FLIGHT)

SRB ACTIVITY	MANHOURS	COST
SRB PROCESSING	18,603	\$ 311,191
SRB STACKING	10,240	181,008
VAB INTEGRATION	5,095	88,728
PAD PROCESSING	18,575	343,842
SRB SHOPS/SE MAINT	3,378	54,264
SRB OPS SUPPORT	6,898	179,466
INTEG OPS SUPPORT	7,961	164,167
PSF - MAINT	2,818	54,488
VAB - MAINT	4,639	90,196
PAD/MLP - MAINT	276	5,661
SAFETY	5,377	114,630
OVERHEAD	4,183	90,407
SPC (LSOC) SUPPORT		
SRB PROCESSING	1,120	23,016
SRB STACKING	784	16,111
VAB INTEGRATION	254	5,220
PAD PROCESSING	5,704	109,146
OPS SUPPORT	814	14,888
GRUMMAN	3,997	78,936
	<u>100,716</u>	<u>\$1,925,365</u>

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Space Operations Company



TABLE 2

LIQUID ROCKET BOOSTER (LRB) KSC IMPACT

MAY 10, 1988

LRB PROCESSING MANHOURS AND COST

SKILL MIX	RATIO	MANHOURS	COST
LRB PROCESSING			
VAB OPS		11,744	
PAD OPS		3,632	
		4,680	
TOTAL TECHNICIANS	1.00	20,056	\$ 355,392
ENGINEERING	0.89	17,850	366,814
FAC & GROUND SUPPORT	1.14	22,864	393,258
LOGISTICS	0.53	10,630	172,095
QUALITY	0.38	7,621	139,393
SAFETY	0.08	1,604	29,346
PP&C	0.22	4,412	78,892
OVERHEAD	0.42	8,424	162,574
GRUMMAN	0.71	14,240	281,235
SUBTOTAL		107,701	\$1,979,000
BASE SUPPORT - EG&G	1.60	32,090	\$513,434
NASA - CS	1.92	38,508	847,165
SUBTOTAL		70,598	\$1,360,599
GRAND TOTAL		178,298	\$3,339,599

COMMENTS AND ASSUMPTIONS:

1. MHRS AND COST FOR PROCESSING LRBs FROM RECEIPT THRU LAUNCH
2. ALL SKILL MIXES ARE RATIOED TO TECHNICIANS
3. MHRS AND COST ARE BASED ON THE LRB PROCESSING FLOW
4. EG&G BASE SUPPORT ASSUMES 20% SUPPORTS CARGO AND 80% SUPPORTS SHUTTLE ELEMENT PROCESSING
5. THE NASAKSC CIVIL SERVICE VALUES HAVE THE SAME ASSUMPTIONS AS THE EG&G BASE SUPPORT ASSUMPTION IN ITEM #4
6. A NON-RECOVERABLE LRB IS ASSUMED IN THE ABOVE TABLE

THE SUPERTANKER DESIGN PHILOSOPHY IS:

- 1 Liquid Oxidizer Tank
- 1 Liquid Fuel Tank - preferably Hydrogen
These propellants fulfill ALL Propulsion, Power, and Cooling requirements
- Fuel and Oxidizer tanks structurally separated
- Propulsion is derived from a single engine cluster
- One or more engines are jettisoned at staging velocity along with thrust structure

SUPERTANKER DESIGN PHILOSOPHY BENEFITS:

- *Increased flight rate over 350% with reduced operations manpower and facilities*
- *Eliminates harmful exhaust products*
- *Enables commercial vehicles to be competitive on the world market*
- *Flight Safety and Reliability are greatly increased*
- *Ground Safety is greatly improved*
- *Potential for Space Station Component*
- *Unmanned Cargo Shuttle can be added to existing fleet without sacrificing Manned Shuttle Flights*
- *Increased probability of launching when planned*

RELIABILITY

SOLIDS

Demonstrated - 0.9765

2 Failures in 100 Boosters

1 Failure in 25 Missions
(2 Boosters/Mission)

15 Full-Up Hot Fire Tests

LIQUIDS

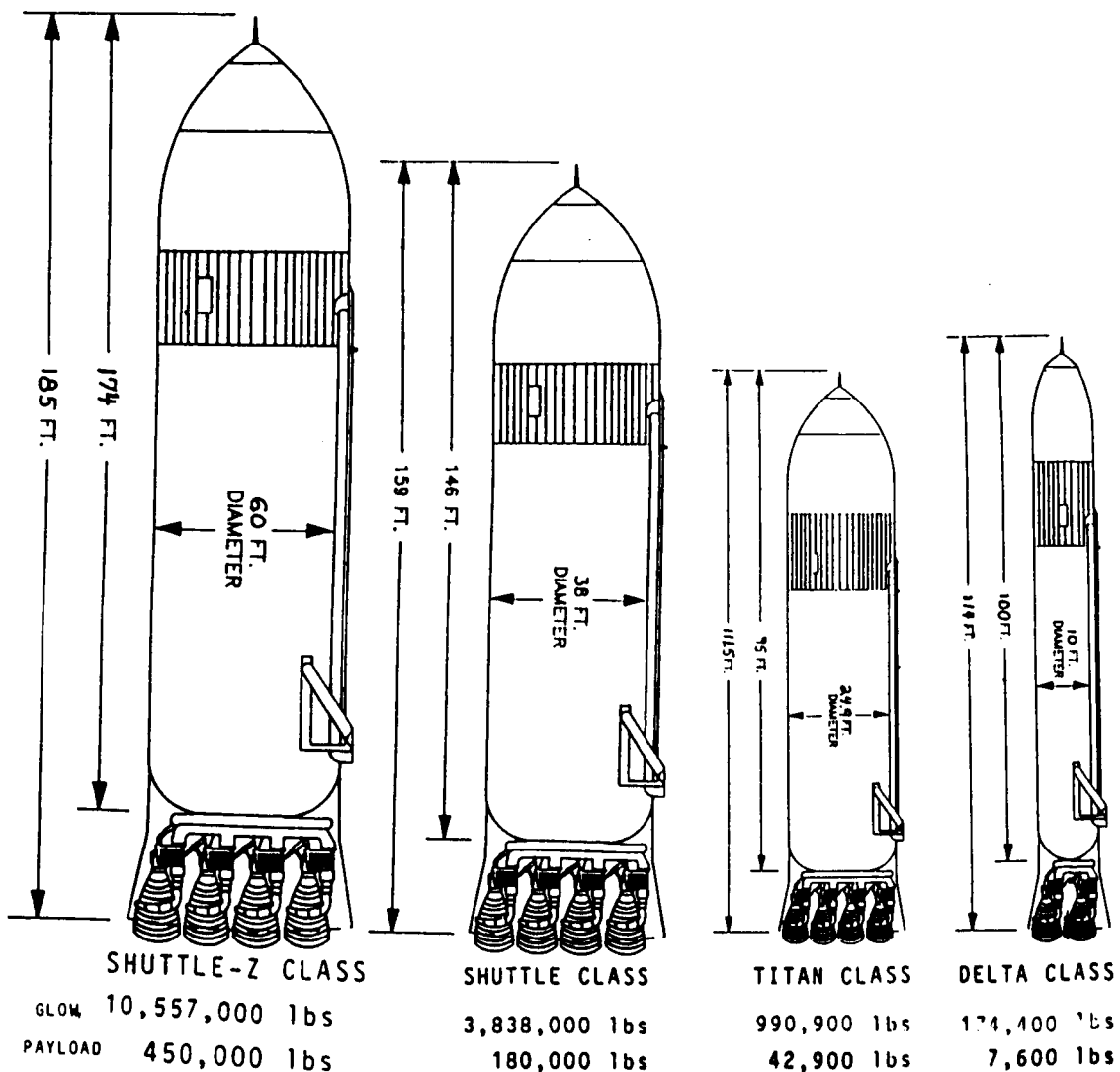
Demonstrated - 0.9935

<1 Failure in 100

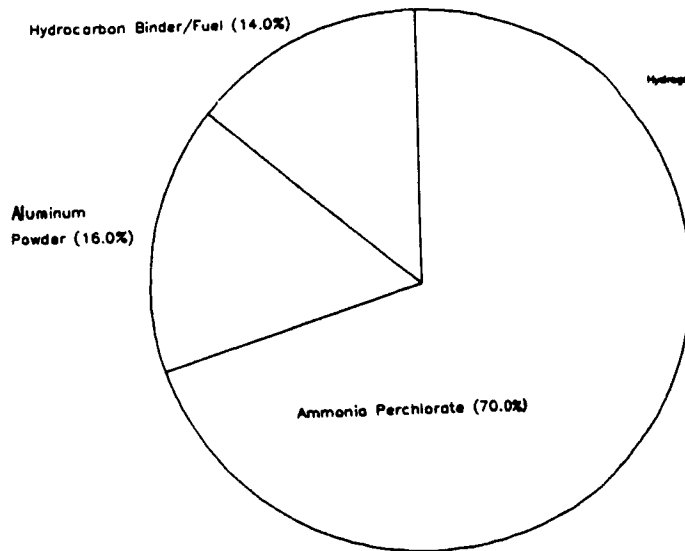
1 Engine Failure in 50 Missions
(3 Engines/Mission)

1350 Full-Up Hot Fire Tests

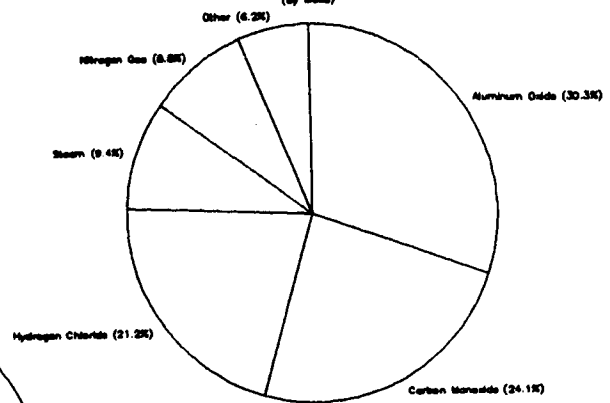
Theo. Design Reliability 0.9997



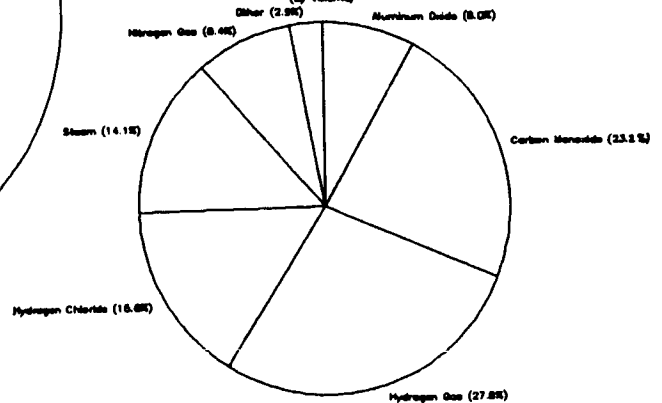
2,225,000 lb Propellant
(By Mass)



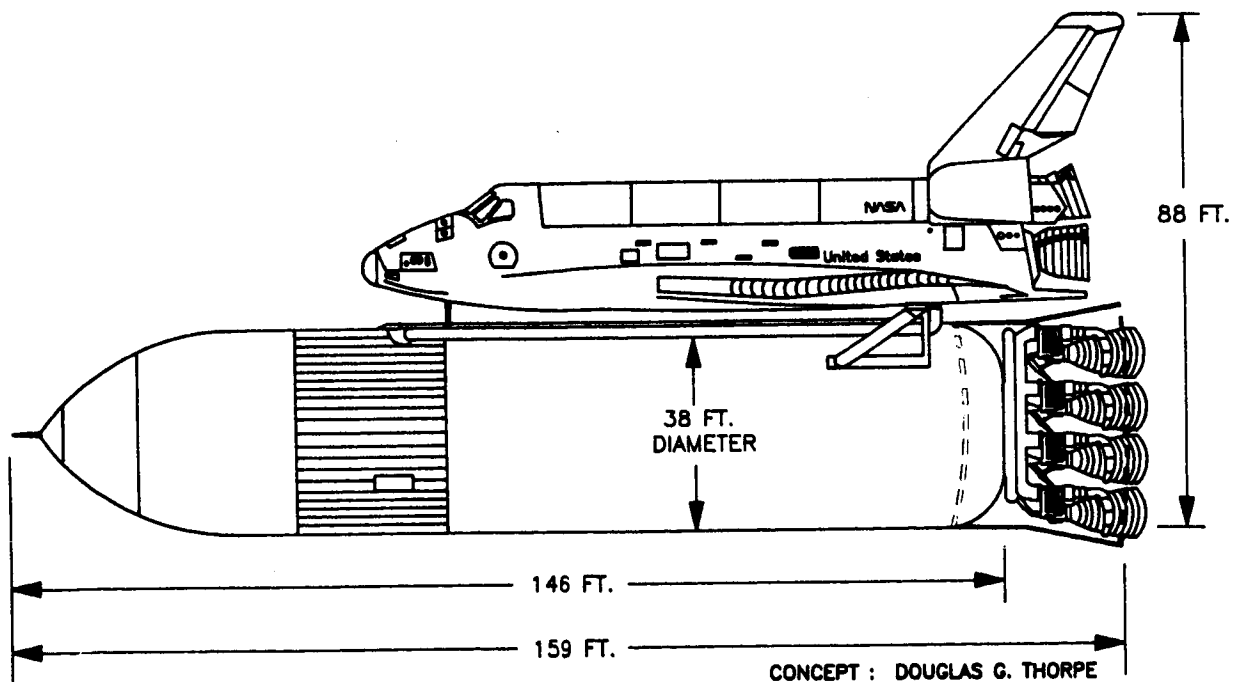
Exhaust Products
(By Mass)



Exhaust Products
(By Volume)



SUPER-TANKER SPACE SHUTTLE



CONCEPT : DOUGLAS G. THORPE
CAD : JOEL E. STIEGLITZ